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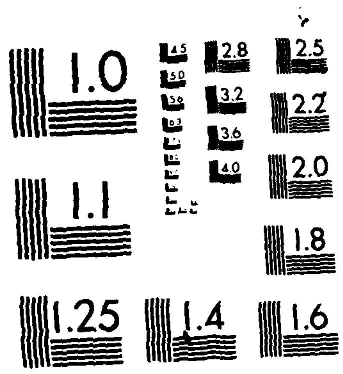

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THE SCIENCE OF AND ADVANCED TECHNOLOGY FOR COST-EFFECTIVE MANUFACTURE OF HIGH PRECISION ENGINEERING PRODUCTS

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AUTOMATIC GENERATION OF PROCESS OUTLINES OF FORMING AND MACHINING PROCESSES

PREPARED BY
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AUGUST 1986

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This report describes a method and a system for automatic generation of multi-technology process-outlines. A process outline is a sequence of operations leading from the raw workpiece to the required finished part. The method is applied to axisymmetric parts produced by a set of deep-drawing and machining processes. The method, the plan synthesis tactics and the forms of representations are based on the study and evaluation of the technological knowledge. The input is a CAD representation of the required finished part and the output is the highest priority process outline to manufacture the part. The process plan is developed, backwards, in two steps. In the first one a preform is designed and in the second a process plan to manufacture it is generated.

The preform of a formable type, out of which the part can be machined, is produced by computational geometry heuristics. The deep-drawn preform is a uniform wall-thickness that circumscribes the required part while complying with recess radii constraints. The circumscription tactics can be expanded to non-uniform wall-thickness cups. The resulting preform is converted into a CAM representation and
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manipulated by the subsystem that generates forming process outlines. That system is a plan synthesis rule-based system that employs three mechanisms to generate the nodes along the most likely solution paths. These mechanisms define the system in abstract terms and make the deep-drawing and machining one instantiation of a more generalized method.

The first mechanism is the main plan synthesis tactic, *Generate & test and rectify*. This tactic controls the automatic design of the preform and the generation of the deep-drawing process outline. Its basic premise is: If initial hypothesis fails the plan generator first attempts to rectify it. Regeneration of a new hypothesis is sought only if rectification also fails. The second mechanism is the *hierarchical structure* of rules. This structure stipulates that each technological rule is an instantiation of a higher level conceptual rule. The third mechanism, *automatic* construction of the inclusive *test rule* generates the "test" within the "generate and test" part. The appropriate test is tailored to each instance of material, geometries and sequence of forming processes.

Both parts of the system are implemented in Prolog, under the UNIX operating system at Purdue University. Experiments demonstrate that the methods employed produce sound plans for the specified domain.

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This report represents, with minor changes, the thesis submitted by Mr. Gad Eshel to the Faculty of Purdue University for the award of the Degree of Doctor of Philosophy.

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M. M. Barash served as Major Professor for the thesis; he is a member of the faculty of the School of Industrial Engineering at Purdue University. W. Johnson was Faculty Associate on the project; he is a Visiting Professor of Engineering at Purdue University.

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Moshe M. Barash
Principal Investigator

C. Richard Liu
Principal Investigator

*Member companies of CIDMAC are:

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NOMENCLATURE

Nomenclature specific to chapters 2, 3 and 7 is reiterated at the beginning of those chapters.

Subscripts and **superscripts** (designating a general x):

x_0 - initial, at the beginning of the operation.

x_{cur}, or X_{Cur}, - current.

x_C - pertains to compressive state.

x_D - pertains to the design stage.

x_f, or x_F, - final, at the end of the operation.

x_G - goal state.

x_H - pertaining to the hypothesis.

x_i - serial number.

x_I - initial.

x_N - new.

$x_{1,2,3}$ - principal directions for stress/strain (Fig. 3-3).

$x_{x,y,z}$ - axes in Cartesian system.

$x_{r,h,\phi}$ - coordinates in cylindrical system (Fig. 3-3).

x_{max}, x_{min} - extremal values of x.

$\bar{x}$ - effective, representative, or: mean, average.

$\dot{x}$ - derivative (default: w.r.t. time).

x_T - tensile stress regime.

x_U - pertains to ultimate strength, onset of instability.

$x_{(f),(w),(b)}$ - flange, wall bottom, - denoting regions of the cup.

Symbols:

$|$ - "provided that the set of conditions to the right is satisfied".

$\leftarrow$ - logical "imply", to the left. ($\{P \leftarrow Q\}$ means: Q implies P).

$\rightarrow$ - logical "imply", to the right. ($\{P \rightarrow Q\}$ means: P implies Q).

, - logical **and**, in clauses.

; - logical **or**, in clauses.

$\wedge$ - logical "and".

$\vee$ - logical "or".

$\sqcup$ - start and end of a procedure.

|| - parallel. /* - start of a comment within a Prolog procedure.

{ X } - a set of elements X, or a set of procedures X, being processed sequentially. "{" stands for **begin** and "}" for **end**.

[X] - list or ordered set X.

X↑ - the value of X goes up.

X↓ - the value of X goes down.

☞ - "implies that".

Terms

α - die-bend angle, determines conicity.

β - stress ratio: $\sigma_{wall(\epsilon_y=0)}$ / $\sigma_{flange(\epsilon_r=0)}$.

ΔR - Normal Anisotropy ($\Delta R = \epsilon_t / \epsilon_{length}$).

ϵ - strain. $\bar{\epsilon}$ - effective strain. $\dot{\epsilon}$ - strain rate.

η - efficiency of work: $Work_{ideal} / Work_{actual}$.

θ - an angle of a small element in plane.

μ - coefficient of friction.

σ - axial stress (+ tensile, − compressive).

$\bar{\sigma}$ - representative stress (root mean square of shear stresses).

σ_U - as subscript: ultimate strength, (tensile or compressive).

$\bar{\sigma} / \bar{\epsilon}$ - Stress-Strain relationship.

τ - shear stress.

ϕ - diameter.

ψ_i - angles in redrawing.

A_i - general constants, explained in the context they appear.

ACDP - Automatic Circumscription by a Deep-drawable Preform.

AGTR - Automatic generation of the inclusive Test Rule.

AI - Artificial Intelligence.

B - general constant, or: coefficient (as in stress strain relationships, e.g. $\sigma = B\epsilon^n$).

b - the slope of the true_stress - natural_strain curve (approximate in

FEM - finite element method.

FLC, FLD - Forming Limit Curve, Forming Limit Diagram.

FP - forming process.

FTR - Flange Wall-Thickness Ratio: t_{flange}/f.

G&T - Generate and Test.

G&TR - Generate & Test and Rectify.

GPP - generative process planning.

GT - Group Technology.

Head - first element of a list.

h - height.

HR - Height to Diameter ratio in a cup: h_{cup} / d_{cup}.

H&T - Hypothesize and Test.

Int/*int* - internal (in Prolog-like relationships).

ITR - Inclusive Test Rule.

k - number of elements of the medial of a cup.

k - shear strength.

K, K_1 - coefficients.

KB - Knowledge Base.

L - a prefix for "Limiting":

- LD - Limiting D.
- LDRR - Limiting DRR (minimum and maximum values).
- LDRT - Limiting DRT (minimum and maximum values).
- LFTR - Limiting FTR
- LHR - Limiting HR.
- LPRR - Limiting PRR (minimum and maximum values).
- LPRT - Limiting PRT (minimum and maximum values).
- LRD - Limiting RD.
- LRR - Limiting RR.
- LSR - Limiting SR.
- LTap - Limiting Tap.
- LTR - Limiting TR.
- LTT - Limiting TT.

LHS - Left Hand Side.

m - strain rate exponent in the stress - strain-rate function: $\sigma = C\dot{\epsilon}^m$.

or: Hill's experimental non-quadratic exponent in the yield criterion. For in-plane isotropic, plane stress conditions, with $\sigma_3 = 0$:

$$|\sigma_1 + \sigma_2|^m + (1+2R)|\sigma_1 - \sigma_2|^m = 2(1+R)\ \sigma_U{}^m.$$

or: Tresca yield criterion modified constant, default: $m = 1.1$.

medial - the skeleton of a body. In 2D shapes it is the thickness centerline and the thickness center surface in 3D shapes.

n - strain exponent in the stress - strain relations: $\sigma = B\epsilon^n$ or: $\sigma = \sigma_0 + B\overline{\epsilon}^n$.

or: number of vertices or sides of a simple polygon.

O(X) - complexity in the order of X.

Fac - Facing; in context of the determination of the reference surface.

P - plan, or: Punch force.

p - external pressure.

Par/*par* - parallel (in Prolog-like relationship).

PLL - Piecewise Linear Line.

PM - process model or: process modeling.

PO - process outline.

PP - process plan or: process planning.

PPF - process planning of forming processes.

PPM - process planning of machining processes.

PR - Punch-rounding.

PRR - Punch-profile Radius to Punch-stem Ratio: $d_{\text{punch stem}} / r_{\text{punch rounding}}$.

PRT - Punch-profile Radius to Thickness Ratio: $r_{\text{punch rounding}} / t$.

r - radius.

r - radius of a sphere.

R - Planar Anisotropy: $R = \epsilon_{\text{width}} / \epsilon_{\text{length}}$. $\overline{R} = (R_{0°} - 2R_{45°} + R_{90°}) / 4$

.

R Rule - Rectify Rule.

RBS - Rule-Based System.

RD - Redrawing Ratio: $d_{\text{stage}_i} / d_{\text{stage}_{i+1}}$.

RHS - Right Hand Side.

RR - Reduction: $(d_{\text{stage}_i} - d_{\text{stage}_{i+1}}) / d_{\text{stage}_i}$.

S - Segment.

exponential curves).

bottom - the downmost element in cup (see Fig. 3-1).

C - coefficient (as in stress-strain_rate relationship: $\sigma = C\dot{\epsilon}^m$).

or: Circumscribing, (e.g. c-polygon - circumscribing polygon).

or: subscript denoting: compressive.

C-P - Computation Parameter.

CAPM - computer aided process modeling.

CAPP - computer aided process planning.

CC - Circumscribing Cup.

CG - Computational Geometry.

CPP - Computer driven Process Planning.

CPPF - computer driven process planning of forming-only processes.

CPPM - computer driven process planning of machining-only processes.

CTR - Category Test Rule.

d - Diameter.

det - determine (in Prolog-like relationships).

die impact line - the line separating the zone in which drawing is the main mode of deformation from the one in which stretching prevails (see Fig. 3-1).

D - Draw Ratio: $d_{blank} / d_{final\_shell}$.

D Rule - Design Rule.

DR - Die-rounding.

DRR - Die-rounding Radius Ratio: $d_{die\ throat} / r_{die\ rounding}$.

DRT - Die-rounding Thickness Ratio: $r_{die\ rounding} / t$.

e - nominal ("engineering") strain.

E - Young's modulus.

$E_{buckling}$ - buckling modulus: $E_{buckling} = 4\ E\ b \,/ \left(\sqrt{E} + \sqrt{b}\right)^2$.

ES - Expert System (in Prolog-like relationships).

Ext/*ext* - external (in Prolog-like relationships).

edge - the part of the flange that may be supported by a blankholder.

f - width of the edge.

flange - the topmost element in a cup if it is perpendicular to the axis of symmetry.

F - force.

FDM - finite differences method.

SR - Height Ratio of a Spherical Element: $h_{spherical\ element} / d_{dome}$.

Surf/*surf* - surface (in Prolog-like relationships).

T - subscript denoting: tensile.

t - Wall Thickness. Default: nominal wall thickness.

TK - Technological Knowledge.

T-P - Test Parameter.

T Rule - Test Rule.

Tail - The remaining chain of a list with the Head removed.

Tap - Severity of drawing tapered cups (Conicity Severity).
Defined as: Tap = $LHR_{vertical\ cup} / LHR_{tapered\ cup}$

TR - Wall Thickness Ratio: $t_{deformed\ zone} / d_{deformed\ zone}$.
or: specific T Rule.

TT - Wall Thickness Thinning, defined as: e_t.

U - as a subscript, denotes: ultimate (strength), onset of instability.

UE - ultimate natural strain a particle in the $cup_{current}$ undergoes, with regard to its initial shape, as a part of the blank: $\epsilon_{U_{Max}}$.

V - vertex.

W - work. w - work per unit volume.

wall - the region between the flange and bottom in a cup.

WP - Workpiece.

Y - yield strength.

Drawings

Axisymmetrical parts are drawn by either the entire cross section and the axis of rotational symmetry, or by the right half of the cross section and the axis of rotational symmetry.

Dimensions are in inches unless otherwise indicated.

ABSTRACT

This report describes a method and a system for automatic generation of multi-technology process-outlines. A process outline is a sequence of operations leading from the raw workpiece to the required finished part. The method is applied to axisymmetric parts produced by a set of deep-drawing and machining processes. The method, the plan synthesis tactics and the forms of representation are based on the study and evaluation of the technological knowledge. The input is a CAD representation of the required finished part and the output is the highest priority process outline to manufacture the part. The process plan is developed, backwards, in two steps. In the first one a preform is designed and in the second a process plan to manufacture it is generated.

The preform of a formable type, out of which the part can be machined, is produced by computational geometry heuristics. The deep-drawn preform is a uniform wall-thickness cup that circumscribes the required part while complying with recess radii constraints. Th circumscription tactics can be expanded to non-uniform wall-thickness cups. The resulting preform is converted into a CAM representation and manipulated by the subsystem that generates forming process outlines. That system is a plan synthesis rule-based system that employs three mechanisms to generate the nodes along the most likely solution paths. These mechanisms define the system in abstract terms and make the deep-drawing and machining one instantiation of a more generalized method.

The first mechanism is the main plan synthesis tactic, *Generate & test and rectify*. This tactic controls the automatic design of the preform and the generation of the deep-drawing process outline. Its basic premise is: If initial hypothesis fails the plan generator first attempts to rectify it. Regeneration of a

new hypothesis is sought only if rectification also fails. The second mechanism is the *hierarchical structure* of rules. This structure stipulates that each technological rule is an instantiation of a higher level conceptual rule. The third mechanism, *automatic* construction of the inclusive *test rule* generates the "test" within the "generate and test" part. The appropriate test is tailored to each instance of material, geometries and sequence of forming processes.

Both parts of the system are implemented in Prolog, under the UNIX operating system at Purdue University. Experiments demonstrate that the methods employed produce sound process plans for the [illegible]

1. INTRODUCTION

1.1 Automatic Process Planning and Multi-Technology Manufacture

Process planning systems are designed with the intention of automating as many functions of the system as possible. That intention notwithstanding, most of the existing process planning systems are actually computer *aided.* The most common form of computer aided process planning is implemented in variant process planning. In variant process planning systems a part is assigned a family and the family is assigned a standard plan. The standard plan is retrieved and manually parametrized, or modified, to adapt it to the particular workpiece. While automatic parametrization can be incorporated into such systems, automatic modification requires a higher level of intelligence. The intelligence is basically of the order of that necessary to generate a new plan. Generative process planning stipulates that process plans are created from scratch. Contemporary generative process planning systems require some degree of user intervention, especially in the early stages where the outline of the plan is determined. Automatic process planning is thus the ideal, fully automated, interaction-free, generative process planning.

Progress in automatic process planning has thus far been confined to metal removal processes only. Automatic process planning for machining-only operations is best attained by *de-machining.* De-machining stands for building up the removed material over the required finished part, reversely emulating the removal of the metal. As for metal forming processes, there has not yet been developed a corresponding basic process planning strategy. "de-forming" may, similarly to "de-machining" designate the reverse deformation, but it has not yet been formalized for automatic process planning of forming processes.

Interest in computer aided process planning of forming processes dates back to the time when ideas about automatic process planning in machining

emerged ([Berra]). First system ([Niebe]) was merely a group technology (GT) based retrieval system. It emulated the industrial practice of assigning a process to a given part. A part is manufacturable by a certain forming process if its features are within the scope of application of that process. That scope of application is determined in accordance with empirical knowledge and a collection of "rules of thumb". Salient measures of the scope include: size of part, class of geometry and configuration, material type, quantity required and cost of manufacture. An accurate tabulation of these measures requires an exhaustive formulation of all possible combinations of the aforementioned variables. Obviously, the scope of possible combinations, with more than 30000 materials, hundreds of geometry classes and groups of sizes, surpasses the experience of any individual. GT classifications for forming processes have thrived in the 60's, notably in the Germanies, as aids to preform design and process selection. Examples include: "Spies", "Gurevich", "Walter" and "Auerswald" for forging, "Puschman", "Aachen-Opitz" and "Salford" for sheet metal parts, "Stuttgart" for flow turning and "Malek" for foundry products ([GallaKn]).

Non-GT computer aided process planning in forming processes has actually been GT-based too. Boeing's sheet metal process planning system (BUCCS) and Brigham Young's decision tree system [AllenSm] represent this type. Some progress has been made in the development of computerized aids for the parametrization and testing of forming processes (e.g. [Lee], [OhLA81]). Nonetheless, computer driven process planning for forming processes has largely remained a computer-aided and geometric-only discipline.

It is generally accepted that analytical solutions to a forming process are impossible to obtain unless geometry and boundary conditions are outstandingly simple. Indeed, few fine grain analyses are used in industrial practice or embedded in computer programs that solve a particular forming problem ([BoerJ]). Industrial practice relies mainly upon islands of empirical knowledge, utilized in an "expert"-like fashion. With the evolution of finite element analysis (Kobay85]), special purpose programs designated to determine the local strains during the deformation provide a means to more accurately predict formability limits.

As a result of the analytical complexity, process planning in forming processes is much more difficult than process planning in machining-only processes. In this sense, formability is only a partial substitute to machinability. A deformation can be executed within a certain range of parameters. The range means that threshold preconditions have to be satisfied so that incipient flow can be initiated, and that once flow has started, the accumulated history of the deformation zone affects feasibility, not just the current shape and mechanical properties . Expansion of the machining-based automatic process planning to the domain of forming processes requires first that some basic research issues be solved. These include:

— Differentiation between the principal part of the plan of manufacture and the detailed design and parametrization of parts.

— The role of feasibility in the actual generation of one forming operation, and ultimately in the entire process plan. It is the feasibility of having the process started and of producing the required end-features as well as of successfully completing the deformation.

— Prototyping the technological knowledge of one forming process and a family of forming processes.

— Modeling the automated generation of a sequence of forming processes.

— The generation of multi-technology process plans, e.g. of some forming operation and complementary machining. This introduces the problem of determining the preform the part will be machined from as an integral part of process planning.

The nature of the technological knowledge, even for machining-only process plans brought many researchers to the conclusion that the initial stages of process planning stipulate *creativity* ([SpurKt]), implying that a fully automatic process planning system is not attainable ([Nau82]). However, developments in artificial intelligence (AI) - ***automated reasoning*** and ***plan formation*** - and their application in *expert systems* may provide the knowledge of forming processes with capabilities previously attributed to human beings only. A preliminary evaluation of the nature of the technological knowledge is thus a prerequisite to an investigation of process planning in forming processes. Such research

indicates that many of the characteristics of the forming processes knowledge make it amenable to be manipulated by rule based system (RBS).

Rule-Based Systems have been found to be a good fit for plan generating systems (e.g. [DavisKi], [Nilss80]). Automatic generation of process plans is basically a task of the same class. The *backward* (or: goal driven, top down) reasoning method, in rule based systems, corresponds to reverse manufacturing. It starts from the goal, and tries to match the database by generating and satisfying subgoals.

With the knowledge being organized, a strategy for utilizing it to generate the feasible process plan has to be developed. Since an outright solution is not attainable, some form of problem reduction is needed. Problem reduction implies creating and verifying subgoals. One of the techniques of problem reduction is "hypothesize & test" (H&T) ([Nilss80], [Wos]). The H&T strategy - (a term usually applied to scene analysis) - or its plan formation counterpart; "generate & test" (G&T), offers a real-life-based approach to plan formation. Forming the hypothesis is another matter; although some research in mechanizing the hypothesis formation has been carried out ([Hajek]), application can not yet benefit from it. As it became clear that generalized problem solvers did not furnish useful tools for automatic planning, more sophisticated, but at the same time domain-dependent systems have been sought. Techniques for such planners include *hierarchical planning* (ABSTRIPS [Sacer74]) and NOAH [Tate77]) and *plan amendment* (DCOMP [Sacer75], [Sacer79]).

Recent extensive activity in Battelle Labs. is the attempt to harness RBS to process planning of forming processes, especially in forging. One system developed there, FORMNG ([Badaw]), generates the sequence of closed die forging operations for axisymmetrical parts, given a particular billet. Other rule based systems developed there prototype the design of special-purpose preforms and blockers for closed die forging. Nonetheless, the application of RBSs to generate process plans of forming processes has thus far been confined to improving the data manipulation mechanisms. A theory that would apply a strategy of generating process plans to the semantics of the knowledge of the particular forming process is still sought. This research is aimed at contributing towards this goal.

1.2 Research Objectives

The objective of this research is to formalize a method for the automatic generation of multi-technology process plans for the manufacture of metallic workpieces. Since process planning is a phenomenological discipline, the method has to be formulated on the basis of a special application. Taking into account the differences in the technological capabilities of processes the method will be significantly modified when applied to other sets of processes. Hence, the process of analyzing the technological knowledge and formulating the process planning method is as important as the outcoming product.

The applications which are the objective of this research are:

- Axisymmetric and monotonic parts, produced by deep-drawing and machining.
- Deep-drawing processes that are capable of producing straight-walled, flanged, tapered or hemispherical, stretched or drawn deformation zones.

It is presumed above that if machining is used during the forming stage, it is limited to auxiliary operations only, mainly to qualify surfaces for the next deformation.

This planning system would be employed after a preliminary evaluation can reveal that the candidate processes are applicable. With the set of participating processes given and the presumption about use of machining to remove material from a part produced by forming operations, three research tasks have to be accomplished to attain the automatic generation of multi-technology process-plans, namely:

1. The essence of the principal part of the plan of manufacture (process outline) w.r.t. the rest of the details of the process plan.

2. Automatic generation of the formable preform out of which the part can be machined. In the context of forming and machining, machining processes are applied to out the preform that has been produced by the set of forming processes, thus producing the part in its final form.

3. Automatic generation of the forming-only process plan to manufacture the preform.

The study of the feasibility of constructing a multi-technology process planning system focuses on the forming part. Although no system has yet been implemented in industry, the technology of automatically planning the machining of monotonic axisymmetric parts has attracted much of research and may be considered conceptually solved. It follows that the opening and crucial part of the research is the study of the technological knowledge of the candidate forming processes. This study is expected to furnish the investigator with the tactics and logics needed to design the system.

A preparatory study of the technological knowledge has indicated that the following techniques can be used:

1. The automatic design of the preform corresponds to automatic circumscription of the part by a formable preform. Computational geometry will be used to obtain the circumscribing preform while the part will be represented as a monotonic polygon. The output of this stage is a CAM description of the circumscribing preform - the cup. Since no conclusive procedure for optimum circumscription was found and several heuristics may be attempted, a RBS promises to provide a useful structure for their manipulation.

2. The automatic generation of the forming-only process plans is perceived as an AI plan synthesis system. The supervisory plan synthesis tactics will be derived from the technological knowledge.

In each stage of the research, the overall intent is to set a pattern of study that can be applied to broaden the set of applicable processes, and not only to ad-hoc build a system for machining and deep-drawing.

1.3 The Domain of Instance: Industrial Environment, Parts, Processes

The multi-technology process plans are generated for a family of axisymmetric parts that are deep-drawn and subsequently machined. The application and the industrial environment it is typically found in, are elaborated below.

Environment.

The industrial environment of the AGMPO system is the small batch, or one of a kind, technologically advanced manufacturing. The prevalence of this mode is widely publicized and will not be elaborated here. Normally, in this manufacturing environment the processes that may be part of the final process plan are the ones practiced in the plant/enterprise. Thus, expanding the scope of automated process planning to include non-chip-forming processes only, is a real industrial necessity.

Products and Processes:

The end parts are workpieces with rotational symmetry. The family of rotational parts constitutes a major share of the batch manufacturing industry, and thus the need to generalize the scope of products is not exceedingly acute. Furnishing a solution to this family alone is a sufficiently significant task.

The axisymmetry property leads to rotational shape producing processes. Within the forming processes this domain includes: drawing, spinning, extrusion, tube sinking, raw tube-producing processes, and even surface deformation processes like shot-peening and burnishing can be added. The AGMPO system is currently capable of generating deep-drawing processes, each being capable of deforming a set of primitive shape elements to a new set of primitive shape elements. For example: straight cupping can convert a disc to a straight vertical cup, with or without a flange.

Raw material out of which the raw workpiece is cut is assumed to be a standard stock item in a metalworking plant or an 'off the shelf' item in metals warehouses. Its forms, sizes, mechanical properties and metallurgical structure are commercially available, i.e. within the range of products of raw stock producing mills.

Representation of Technology:

Technology is represented realistically; boundaries will be set for normal (conservative) industrial use, and not for the special cases that "stretch" the technology. Assumptions about parts and processes apply to the bulk of them,

but not necessarily to all of them.

Deep-drawn and Machined Parts:

The part in Fig. 1 exemplifies drawn products and parts that are commonly manufactured by a combination of machining and drawing processes. Deep-drawing processes implemented thus far in AGMPO are capable of producing monotonic cups. The machined parts will therefore be monotonic too. This property does not impose a drastic limitation since de-machining to produce a monotonic part is realizable.

In common industrial practice the part of Fig. 1 would have been designed by an experienced designer who would have had taken into account the technology needed to produce it. Proficiency in the technology implies that one masters the capabilities of the processes w.r.t. each of the candidate materials, the preformances of the machines and availability of raw material in stock.

1.4 Preview of the Research

Chapter 2 of this thesis provides the background. It summarizes previous work in the process planning application and data manipulation areas. It also introduces taxonomy that is used throughout the work. The essence of process planning, process planning in forming processes and computer aided process planning in forming processes are research matters by themselves. They are studied and elaborated upon in this chapter to the extent that the first research objective, characterizing the basic part of a multi-technology process plan, is met. Chapter 3 is a detailed study of the technological knowledge of deep-drawing processes. It produces a formulation of the technological knowledge in the form of rules. Chapter 4 outlines the entire AGMPO system and the methodology it is based upon. The system accepts a CAD design of the required machined part and turns out a process outline to manufacture it. Significant AI mechanisms that are not developed within this research but are used by the AGMPO system are briefly described at the end of this chapter. The forming process planning module, AGFPO, uses three main mechanisms to automatically generate deep-drawing process outlines. Before these

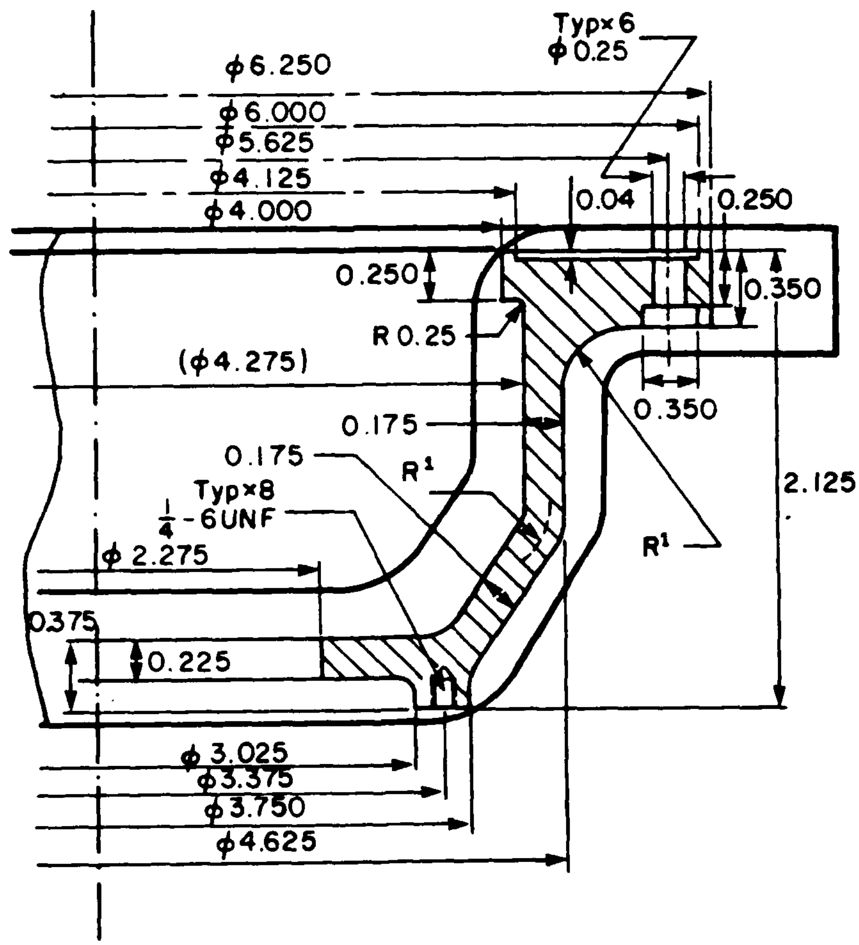

Figure 1-1. Part manufactured by a combination of drawing and machining processes

mechanisms are studied, the methods of workpiece representation and conversions between the representations have to be defined. This is done in chapter 5. The supervisory reasoning tactics; "generate & test and rectify", is used for both the design of the preform and the generation of the deep drawing process outline. Hence it is introduced in chapter 6, before its applications. The automatic circumscription system ACDP, created to produce the preform follows in chapter 7. Chapter 8 gives the description and formulation of another independent reasoning mechanism, the automatic construction of the inclusive test. This mechanism facilitates the automatic generation of the appropriate inclusive test for each hypothesis. Examples of system function and evaluation of the results are given in chapter 9. In chapter 10 the research is summarized and suggests for future work are offered. Some subjects, especially those of the technological knowledge, are of immediate practical applicability.

2. BACKGROUND

Nomenclature

ACDP - automatic circumscription by a deep-drawable preform.

CAPM - computer aided process modeling.

CAPP - computer aided process planning.

CG - computational geometry.

CPP - computer *driven* process planning.

CPPF - computer driven process planning of forming processes.

CPPM - computer driven process planning of machining processes.

ES - Expert System.

FDM - finite difference method.

FEM - finite element method.

FLD - forming limit diagram.

FP - forming process.

GPP - generative process planning.

G&T - Generate and Test.

GT - Group Technology.

G&TR - Generate & Test and Rectify.

KB - Knowledge Base.

O(x) - in assessing complexity: on the order of x.

PM - process model or: process modeling.

PO - process outline.

PP - process plan or: process planning.

PPF - process planning of forming processes.

PPM - process planning of machining processes.

RBS - Rule-Based System.

2.1 Contents of the Background

A study that is designated to produce an automatic process planning method and system requires the merging of extensive knowledge from diverse fields. Three main types of background can be identified:

- the technological knowledge of the processes employed,
- the data manipulation techniques and
- the process planning systems knowledge that facilitates the construction of the system.

The preliminary investigations leading to shaping a method and a system for automatic process planning naturally involve in-depth examination of the state of the art of automatic process planning of machining-only processes. Introductory summaries of this domain can be found in [Weill], [SpurKt], [ChangWy]. Due to the extent and diversity of these studies, only the background having direct relevance to the method developed throughout this research is presented here. This background serves also the taxonomy needs of this work. The discussions about the essence of process planning, process planning in forming processes and computer-aided processes planning of forming processes constitute a study by themselves rather than just a summary of contemporary knowledge.

Process planning, being a phenomenological discipline, requires that a study in it be based on the true characteristics of the processes involved. A multi-technology process planning has to include the knowledge of putting together the participation of the various processes. Automatic process planning has thus far been almost exclusively confined to machining only and will not be expanded here. The background will therefore focus on forming process planning and combined process planning of forming and machining processes. The detailed knowledge of the forming process to which the method is applied - deep-drawing - will be studied in the following chapter. It is postulated in this study that a process planning method is not a matter of data-manipulation only, but that the characteristics of the technological knowledge determine the process planning method.

Forming process planning introduces new factors that have to be studied before the detailed design is pursued. One such factor is feasibility. Feasibility in forming can often be assessed only after evaluation of the

sequence of deformations. For the purpose of designing a feasible deep-drawing process, a design practice and workability evaluation procedure are needed. A design practice is designated to handle complex stampings that require a sequence of deep-drawing processes, i.e. *redrawings.* To illustrate workability, principal *process variables* will be considered:

- press power required to bring about flow of metal,
- drawing ratio and
- the completion of an operation without major defects.

The characteristics of forming process planning and the state of the art of computer aided process planning of forming processes are presented in the following sections.

The multi-technology process planning system merges computational geometry (CG) and artificial intelligence (AI) techniques. The CG techniques form the basis of the automatic design of the deep-drawable preform. Works of relevance in CG are outlined below. The principal AI techniques: namely modeling of the knowledge in the form of rules, plan synthesis tactics which are an embellishment of the conventional "generate & test" and backtracking search strategy are characterized in the third section of this chapter.

2.2 Process Planning

Since the method that is sought to be developed in the research is directed to automatically plan a *process outline*, - the basic physical plan of the manufacture of a part - it is first necessary clarify what is process planning and what is the place of the process outline within it. Aspects of process plan automation, valid with machining-only as well as with forming and multi-technology process plans conclude this section. This discourse will be followed by the characterization of process planning of forming processes and the state of the art of computer driven process planning of forming processes.

2.2.1 Process Planning: Scope, Structure and Contents

2.2.1.1 Introductory Definitions

Process planning (PP) is still undergoing crystallization as an engineering discipline. Even the term is not yet standardized and the

frequently encountered phrases "manufacturing planning", "material processing" and "process engineering" eventually mean PP. Most of the formalization has thus far concentrated on machining technology only (PP in Machining-only is henceforth abbreviated PPM) and on isolated "islands" of the overall process plan (PP). The following introductory overview is therefore intended to clarify, rather than formalize, notions that are used throughout the discussion of the term.

Process planning is the activity of producing a process plan. The term *plan* has various definitions. Two of these are presented below:

A plan is: "*any hierarchical process in the organism that can control the order in which a sequence of operations is to be performed*"[1], or:

A plan is: "*a directed graph*" [ChangLe].

The following definition is found to best serve the PP context:

"*A plan is a sequence of actions needed to achieve a certain goal determined before acting*".

A plan is distinguished from a *design*.

A design is the set of specifications needed to meet a particular set of requirements, e.g. those of a mechanical workpiece, an electronic circuit, a communication network.

In many cases, including PP, the objective of the plan is to attain a certain design.

PP is not a straightforward activity. Manufacturing processes, on the other hand, are more easily formalized. They have a definite order, procedures to be carried out, and consist of discrete sequential steps. Defining the PP activities in terms of the manufacturing operations is intended to render them formalizable.

PP has drawn a great variety of definitions. One major aspect of the diversity is the scope of PP, i.e. the answer to: "what is included in PP ?".

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1. Miller, G.A., Galanter, E. and Pribran, K.H. *Plans and the Structure of Behavior*, p. 15, Holt, New-York, 1960.

The following attempts to define PP demonstrate this.

Eary and Johnson ([EaryJo], in one of the earliest engineering approaches to PP), state:

> ".. *the function of determining exactly how a product will be made.*"

Chang and Wysk ([ChangWy] version is:

> ".. *that function within a manufacturing facility that establishes which machining processes and parameters are to be used (as well as those machines capable of performing these processes) to convert (machine) a piece part from its initial form to a final form predetermined (usually by a design engineer) from an engineering drawing. Alternatively, process planning could be defined as the act of preparing detailed work instructions to produce a part.*"

In [WyskBM] the following, very general, definition is found:

> PP is "*the subsystem responsible for the conversion of design data to work instructions.*

Weill ([Weill]) expands [WyskBM] definition:

> " .. *process planning is exclusively concerned with the selection of suitable processes and tools to transform raw materials into a finished product according to the design drawing. ...process planning can therefore be defined by the methods and the sequence of machining a workpiece to produce a finished component to design specifications.*"

In view of the above, and of the underlying intent to expand PP to cover also nonmachining processes, the following informal definition is proposed hereby:

> *A PP is the sequence of metalworking operations, each specified to the desirable detail, excluding managerial aspects, to convert a given raw workpiece to a required finished part.*

Some of the building blocks in the above definitions and other prerequisites intended to be used in the forthcoming discussion will be first clarified.

Part - the finished product, as specified by the design. Given in a part print and complementary specifications.

Workpiece - a partially finished part. A finished workpiece is a *part.*

Stock - standardized piece of raw material the processing starts with, e.g. bar, sheet, tube, billet.

Raw workpiece - the metallic workpiece the manufacture starts from. It can be either a stock material or a partially finished part.

Process - Definition by example: drilling, gundrilling, counterboring, closed-die forging, ring rolling, etc. .

Technology - a discipline of processes working on the same principle, e.g. machining, forming, sheet-metal forming, heat-treatment, casting, .. .

Element - the basic metalworking action producing one change in workpiece specifications. For example: drilling six equally spaced holes.

Operation - the set of metalworking elements performed in one work-station. Necessary specifications: initial and final specifications of the workpiece and the mapping process.

Plan of manufacture - the entire set of planning activities: the PP and the production management plan.

Multi-technology (composite) process plan - a PP having operations of more than one technology, e.g. forging and machining.

Many references used by process planners describe capabilities of metalworking processes but do not explicitly elaborate process planning practice. The presumption in the following discussion is that process planning is the set of actions producing the process plan. Process planning activities are therefore derived from the contents of the process plan. The PP concept developed here is ***hierarchical, structured and composite.*** The study of the formal structure and semantics of PP is expected to help develop a methodology of producing it.

2.2.1.2 Scope of Process Planning

While metal parts are manufactured by a combination of technologies, PP, as an engineering domain, has largely been confined to machining. PP is henceforth generalized in accordance with the true spectrum of manufacture. Manufacturing processes may be categorized into six "arch-technologies" (adapted from several references):

I. *Primary forming*: original creation of a shape from the molten or gaseous state, or solid particles of undefined shape, e.g. casting, powder metallurgy.

II. *Deforming* or *Forming*: Shape of a given solid body is converted to another shape, without change in mass, material or composition, e.g. forging,

extrusion, bending.

III. *Separating*: Removal of material, e.g. machining, punching, electro-chemical machining.

IV. *Joining*: Uniting individual workpieces to form a subassembly, e.g. welding.

V. *Coating*: Application of thin layers to the surface of the workpiece, e.g. galvanizing, electroplating.

VI. *Changing material properties*: Deliberately changing material properties at a certain point in the manufacturing process by modifying the structure or orientation of particles, or diffusion of other elements, e.g. heat-treatment, nitriding, shot-peening.

The first four groups modify the shape of the workpiece. One way of breaking them into subcategories and principal processes is shown in Fig. 1.

The classification of processes helps in identifying the settings in which valid PPs can be developed. Common PP settings are represented in the paths a PP can take in Fig. 2. The network structure, even for the highly abstract level of technologies and subtechnologies, points to the enormity of the PP space.

The part should be manufacturable by the examined technology, i.e. it should be *machinable* when submitted to PPM and *formable* when the particular set of forming processes is intended to manufacture it. Otherwise the PP activity cannot be accomplished.

2.2.1.3 Dimensions of a Process Plan

The PP, being a plan, is a sequence of operations. The structure and content of each operation are, however, a matter of great diversity. The above proposed definition of PP does not unequivocally elaborate the content of each of the operations. A PP, similarly to other plans, can be characterized in four dimensions:

a. elements of the PP, *b.* specificity, *c.* level of detail and *d.* determinacy.
These dimensions follow:

Elements of a PP:

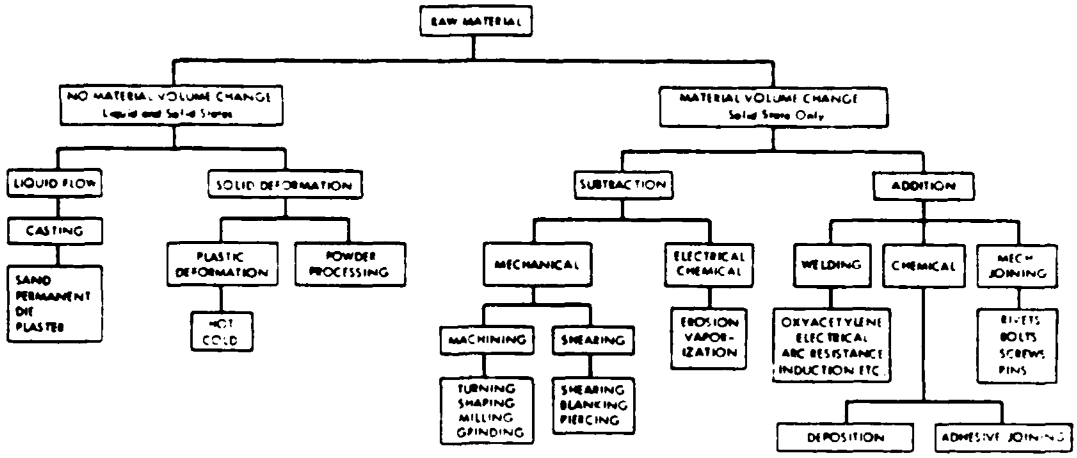

Figure 2-1. Shape changing processes ([MooreKi], Fig. 7-2).

PP is commonly outlined as a list of activities. Since most PP study have been confined to machining only, elements of this list apply to the machining-only domain. The following lists substantiate some of the different perceptions about the contents of PP. The output of each activity is indicated in parentheses.

[EaryJo] stipulates continuous feedback from the PP to the design. Even redesigning is considered a PP activity.

i. Determine basic manufacturing processes (operation code).

ii. Determine order of operations to manufacture a part (operation sequence).

iii. Determine tooling and gaging (tools, gages for inspection).

iv. Determine equipment (machine, work-station).

v. Determine necessary part design revisions originated by manufacturability analysis (part drawing revised).

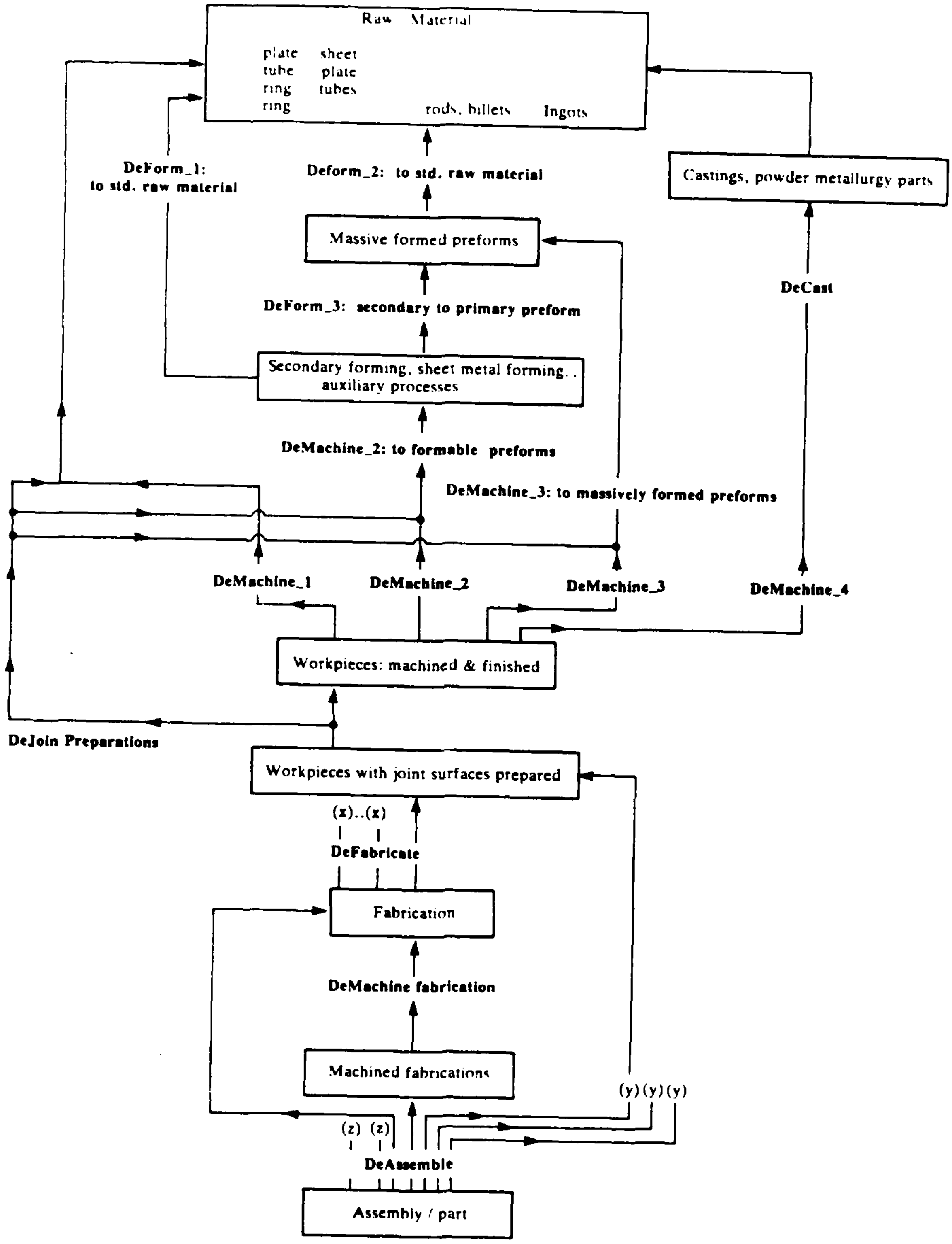

Figure 2-2. Common PP paths at the technology level

vi. Examine functioning of tooling and equipment (tools & equipment).

vii. Estimate duration and cost of operations (duration & cost of operation).

viii. Determine necessary part changes originated by time and cost analysis (part drawing revised).

ix. Redesign part (part drawing revised).

[Weill] elaborates 10 sequential phases through which PPM is carried out:

i. Select processes and tools (process code, tool).

ii. Select machine tools (machine).

iii. Sequence the operations (sequence of operations).

iv. Group the operations (sequence of operations, modified).

v. Select workpiece holding devices and datum surface (fixtures, clamping and datum references of the workpiece).

vi. Select inspection instruments (inspection gages).

vii. Determine production tolerances (specifications of the intermediate workpiece).

viii. Determine proper cutting conditions (cutting parameters).

ix. Determine cutting and non-machining times (duration times).

x. Edit process sheets (final PP forms).

Putting industrial practice together with the above lists, and their kind, yields that a machining-only PP consists of a sequence of operations, each specified by:

- state of workpiece at the end of operation (geometry, including tolerances),
- process of the operation,
- cutting tools,
- machine (or work-station),
- features being machined, their datum surface and clamping surfaces,
- clamping and fixturing devices,
- inspection gages for features produced in the operation,

- machining parameters for each machined feature.
- duration and cost estimates.
- form features that have manufacturability problems (feedback to design).

Time and cost estimates are fully determined by the operative features of the PP. Though their role in the determination of the final PP cannot be overstated, they do not change the physical process and therefore will not be henceforth considered components of PP. Another limitation pertains to the compromises that can be made w.r.t. the initial design. In the forthcoming discourse the part is taken as a constraint. In reality, as pointed out by [EaryJo], feedback to the design is an important function of the process planner.

Specificity:

A PP can be a generalized document or a specific one. A generalized PP is independent of specific stock material, machines, fixtures, jigs, tools and inspection gages. It is given as the sequence of workpiece states, the mapping process, schematic tool geometry and conditions at the tool - workpiece interface. A truly generalized PP should be specified in the following terms:

i. Initial stock material: availability, metallurgical and mechanical properties.

ii. Machine capabilities, e.g. sizes, speeds, desired accuracy.

iii. Clampings: elements that must be machined in one clamping.

iv. Tools: jigs, fixtures, dies, gages, cutting tools, etc. should be specified in terms of their desired functional features rather than full technological design.

v. Alternative routings that are specified as a function of a particular volume of production and take into account features that can be machined independently of others.

A generalized PP has to be *feasible* whereas an instantiated PP has to be also *realizable*. *Feasibility* implies that the operation can be initiated and completed successfully. In machining feasibility exists if, among other things, the feature to be machined is approachable and workpiece hardness can be overcome. A feasible forming operation requires the flow of the metal be

unimpeded, ending in a defect-free workpiece. *Realizability* pertains to the actual execution by given facilities. It always pertains to an instantiated PP. While feasibility is intrinsic to the PP, realizability is external and localized.

Degree of detail:

In industrial practice it is commonplace that portions of the PP are prepared by several functions in the plant. Partial PPs, especially for machining operations in prototype and small batch production, are passed down to the shop, leaving the determination of operative parameters to the foreman or machinist. A practical question is thus: "what are the minimum conditions that qualify a document to be a PP ?". The most relaxed form a PP can be given in is a sequence of specified workpiece geometries and mapping technologies. Another view requires the PP to be detailed down to the level of operations. Usually, the degree of detail of the partial PP reflects the depth of the engineering attention given to the part. It depends upon:

a. Craftsmanship required to successfully accomplish each of the operations.

b. Type of production (prototype, small batch, ... mass production). and machine shop organization (e.g. along product or functional lines).

c. Type of industry (minute details are a must in an aerospace environment).

d. Stage of maturity of the product and the engineering involvement (proven, engineering saturated parts will be highly detailed).

e. Level of standardization in the machine shop.

f. Technologies incorporated (heat-treatment requires a rigorous definition while conventional machining can, more often than not, do without it).

g. Level of computerized automation.

Determinacy of a sequence of operations:

Usually the PP is specified as one deterministic sequence of operations. This custom, though being the result of the limited time a process planner can devote to a single part, eventually works satisfactorily for non-automated shops and parts not depending upon a critical resource. In computer supervised systems, however, and especially in FMSs, alternative routings

enable much better utilization of resources. Alternative routing is a must when critical parts and resources are involved.

Two additional features of the operations composing the PP, namely semantics and formal structure, are further examined in the following sections.

2.2.1.4 Semantics of a Process Plan

A semantic evaluation of a PP focuses on the function and status of the operations. A complete PP starts from *basic stock material*, e.g. sheet, bar, ingot, tube. Allocating the appropriate starting stock material is always a *principal* activity in a PP. Examining the subsequent sequence of operations reveals varying degrees of importance and some *hierarchical* relationships. The *principal* part of the PP specifies the sequence of the *main* intermediate states of the workpiece and the mapping processes. In the context of multi-technology manufacture, an *originating process* is the non-machining process producing the *preform*; the extra material of the preform is later machined away. The *originating process*, which is a sub-process of the PP, may be composed of a sequence of several non-machining operations and incorporate intermediate *auxiliary* machining operations. A *major* or *critical* operation is an operation without which the PP cannot be accomplished.

Not all the operations of a PP are constrained to be executed in a sequence. Some operations are independent of sequences of previous operations. These operations are named here *secondary operations*. Embossing a sheet-metal plate which is not designated to be subsequently machined, or drilling a hole which is not referenced by other surfaces are secondary operations.

Quality assurance and managerial considerations require that *supporting operations* be embedded in the sequence of the manufacturing operations. Inspection packaging and storage are included in the category of supporting operations. These operations do not change the state of the workpiece but may determine different routings.

Auxiliary operations facilitate the execution of a main operation. Intermediate machining between spinning passes, stress releaving heat-treatment between rough and fine machining and grinding welded seams between successive passes fall into this category.

A *qualifying operation* prepares a surface of reference to be later worked on and is thus restricted to metal removal processes only.

These types of operations are shown in the PP example in Fig. 3.

By restricting the PP to physical changes, we have excluded supporting operations from the forthcoming discussion. In real practice, however, supporting operations have as important a role in the routing as have operations changing the physical properties of the workpiece.

2.2.1.5 Formal Structure of a Process Plan

The semantic identification of a PP constitutes the basis for a hierarchical structure since the top, *committing*, level of the PP can be extracted. This level is named here *process-outline* (PO). A PO is the basic technical plan to manufacture the workpiece. It is the *sequence of operations* leading from the raw workpiece to the required finished one. Each operation is designated by the 4-tuple:

- operation # (serial number),
- process (code),
- workpiece specification at the end of operation (geometry and mechanical properties),
- equipment (machine, work-station).

Once the main, committing part of the PP has been established, the *detailed design of the PP* adds the non-principal operations (auxiliary, secondary, qualifying) and the operative aspects of each operation. The details of an operation include the design of jigs, fixtures, tools and gages, the determination of the operating parameters - *parametrizing*, and the detailed description how to execute the operation. In parameterizing a machining operation the speed, feed, depth-of-cut and coolant are determined. The parametrizing of a forging operation consists of determining the force, speed of slide, temperature of the blocker (the preform after the preparatory forging stage), die and lubricant and the surfaces to be lubricated.

In adopting a hierarchical view of the PP it is presumed that it is possible to assess the feasibility of the complete operation before the detailed process design, at the PO stage. A hierarchical view of PP is described in Fig. 4.

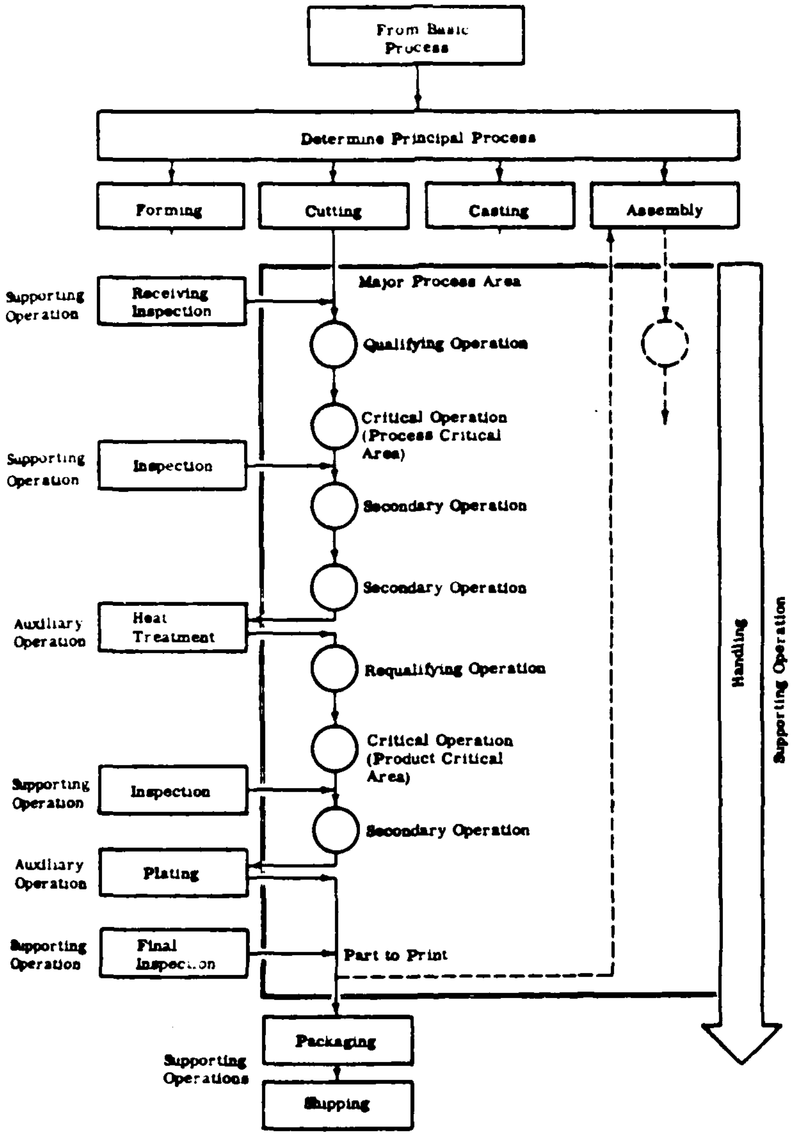

Figure 2-3. Semantics of operations in a PP ([EaryJo], Fig. 191, p. 281)

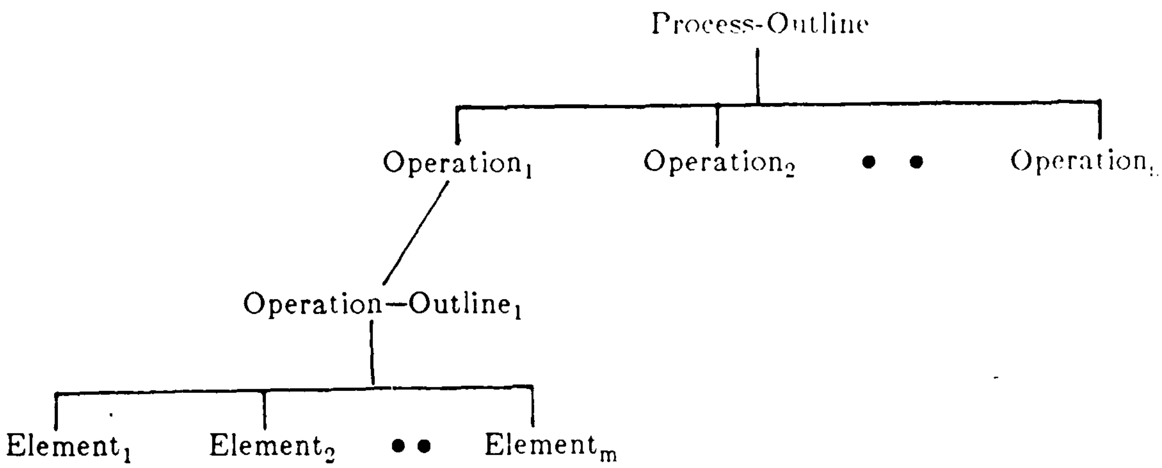

Figure 2-4. Process plan - a hierarchical view

Since an operation consists of a series of elements being performed on the same machine (in machining, preferably, in the same clamping), a sequence of those elements has to be established. An *operation outline* is thus defined along lines similar to the ones defining the PO. An operation outline is the sequence of elements performed on the same machine where each element is the 3-tuple:

- element # (serial number),
- workpiece specification at the end of operation (geometry and mechanical properties),
- facilities (jigs, fixtures and tools in machining, or dies in forming).

Element specification is the lowest operative level and the one that is actually executable. It specifies, in a standardized language understood by the specialists of the particular process in the shop, the exact procedure of carrying the element out. In many cases, somewhat proportionately to the decrease in batch size and especially in nonmachining PPs, the levels of ***operation*** and ***element*** are unified. For example, a deep-drawing portion of the PP that consists of several "elements" - called "passes" in forming - is, in fact, a sequence of operations rather than one operation. It has different tools, set-ups, and operative parameters, and contributes to the strain path, which determines feasibility. Representative PP, in the form of a routing sheet and portions of it, namely process outline, operation outline and element specification are shown in Figures 5 to 8. Fields in which specifications are mandatory are marked with an asterisk (*).

ABC COMPANY	Route Card No. 10	Engineering Department

Product Description

Name: part_ABC

Product #: Ck 53N

Drawing #: 03116-6235

Raw Material: Size 500mm diameter and 3000mm length
Material Alloy steel, high carbon content, quenched to Min 45Rc

Op #	Precedence Code	Operation Description	Spec. #	Fixture	Machine	Time	
						set-up	run*
10	/	Check raw material out of warehouse storage.	10		1	--	
20	/	Cut bar stock into 6 discs.	20		2	10	700
30	/	Trepanning inside of cylinder by EDM.	30	30.10	3	400	740
40	/	Turning: OD faces and inside — rough except for H7 requirements.	40		4		20
50	/	Sawing each disc into 2 rings	50		2		10
60	/	Facing (turn)	60		4		60
70	/	Mill the 4 slots.	70		5		100
80	/	Mill plane and drill side holes.	80		6		120
90	/	Tap the M10 taps	90		6		60

Designed By: ________	Revision
Checked By: ________	Date.

* Unit, minutes

Figure 2-5. A process plan (routing sheet)

2.2.1.6 Generating a Process Plan

Process planning is not a hardware producing activity. It can, however, be formulated in terms of the manufacturing activities, through *inverse-manufacturing*, or *backward process planning* ([BarasFi]). A conceptually inverse process is termed here: *de-manufacture*. For example, "de-bore" a hole means: fill up the "tubes" removed during the boring activity, starting with the outmost cylinder and ending with the tube that makes up the starting surface. Similarly, "de-form" is the inverse forming operation. "DeCup" means: straighten the cup to produce a flat blank.

The hierarchical structure of PP implies that PO generation is the opening and most significant phase of PP. It requires mastery of all the processes that can be performed in the plant, detailed knowledge of material behavior and limitations of available machines. A composite PP is built essentially of two principal subprocesses: the originating sub-process and the finishing one. The machining sub-process starts with a preform, which is the output of the originating sub-process. Components of the PP are hierarchically built to "width" and "depth". "Width" is broadened by adding non-principal operations. "Depth" pertains to the design of facilities and parametrization. The hierarchical structure of PP implies a generation method described in the flow chart in Fig. 9.

2.2.1.7 Computer driven Process Planning

The computer may assume varying degrees of PP automation. The automation level may be viewed as a location along an ***automation axis***. At one end of this axis (see Fig. 10) there are "islands of automation" coordinated by a human-supervisor. In this state the computer serves as an ***assistant***. At the other extreme, in a fully automatically derived PP, all human tasks are fully formalized and the computer totally substitutes human judgement, i.e. the computer becomes the ***expert***. In between, where the contributions of human and computer are equal, the computer is a ***colleague***. The overall involvement of the computer in PP in which the degree of automation is not a-priori known is therefore termed ***computer driven process planning***, and abbreviated CPP. The assistance state is called ***computer aided process planning*** (CAPP) while the extreme state, thus far rather utopian, of fully

PROCESS OUTLINE # 12345		
Part: part_ABC	**Initial Raw Workpiece:** Material: SAE 4340 Condition: O Geometry: ϕ6", length: Min. 4"	**Complementary Documents:**

Op. #	Precedence (default: sequential)	*Process (code)*	Workpiece Specification *(at end of operation)* – document #	Machine
1	/	cut rod (CRod)	12345-1	Hack saw
2	1	Forge blocker (FBl)	12345-2	Press. Min. 300 ton
3	2	Forge preform (FPf)	12345-3	Press. Min. 200 ton
4	3	Heat-treat, Anneal (HT)	12345-4 Heat-treatment Spec. #47-4194	Furnace air. Min. 2000 °F

Designed By: ________	Revision:
Checked By: ________	Date:

Figure 2-6. Process outline

Product: part_ABC **Route Card #:** 10	**Operation Card**
Operations No: 40	

Elements	**Description**
10	Turning outside diameter — side 1. Longitudinal Turning.
20	Turning one step-chucking. Face turning
30	Straighten outside diameter-chucking_2.
40	Turning second step-chucking_2. Face turning.
50	Inside rough turning-chucking_2.

Designed by: ________	Revision:
Checked by: ________	Date:

Figure 2-7. Operation outline

Element Description		
Process: EDM -- Trepanning		
Product: part_ABC **Route Card:** 10 **Operation:** 30	**Name:** Trepanning inside cylinder to form a ring.	**Element:** 10
Machine Type: EDM	**Name:** Siemmens Series 3	

Sketch	**Comments**
Work Holding Std-EDM-01 Tool: Electrode 30-10 Rate of removal: 2 cubic inch/hr.	Required: Heavy-duty EDM **Tank Size:** 700 x 700 x 400 cubic mm **Amperage:** 100amp **Machining Time/Unit** - 740min

Parameters	**Electrode**
Voltage: 110v	Copper type -- brazed
Frequency: 120Hz	Outer diameter: $\phi 228^{+0.5}$
Dielectric: Kerosene	Width: 1/32 inch
Flow pressure: 211mm to 482 kPa	Length: 500mm
Drive Gap: 0.05mm	(See sketch for tool electrode)
Polarity: Workpiece-positive	
Current: 30amp	
Current Amptitude: Jt, Jp, Jr Jt = 3amp	

Designed By: ____________	Revision:
Checked By: ____________	Date:

Figure 2-8. Element specification

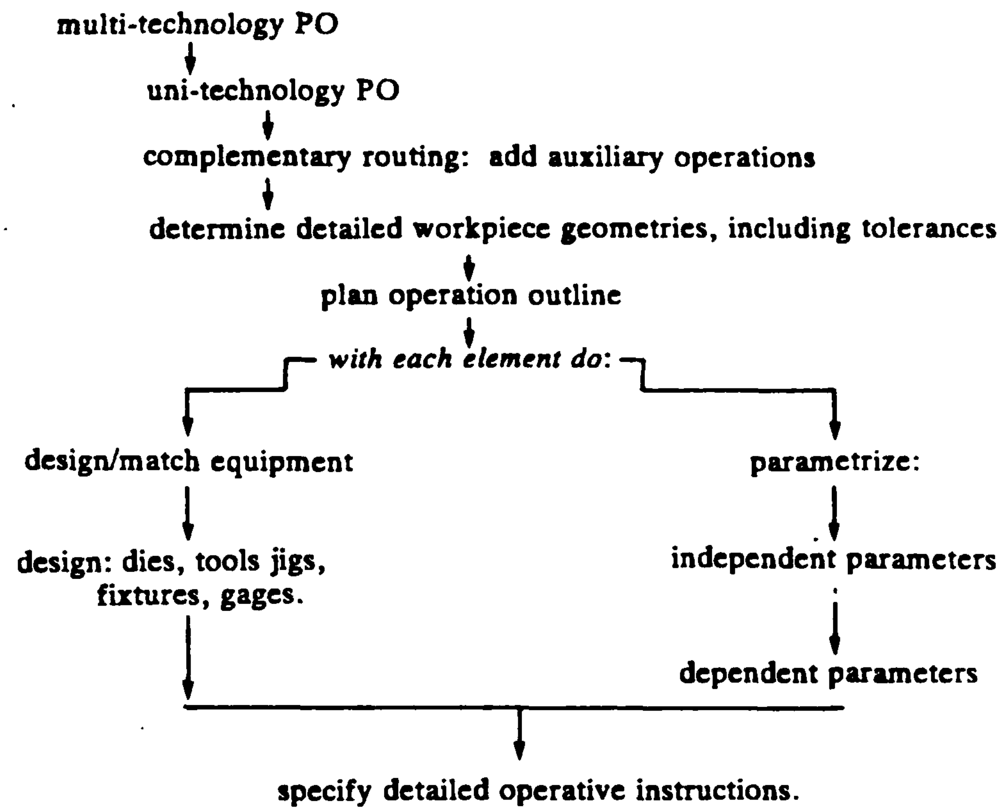

Figure 2-9. A schematic flow, feedback not included, of process planning activities

automatic production of PPs is called *automated process planning* (APP). APP, though extensively investigated in the last decade, is still far away from realization.

Another dimension of computer involvement in PP is the method of producing the PPs. If an appropriate PP is stored in the database and has to be retrieved then the system is of the *retrieval* or *variant* type. The retrieved plan has, in most cases, to be modified. These systems are called "retrieval PP" (RPP) or "variant PP" (VPP) systems where the "variant" term suggests that the resultant plan is a *variant* of the basic retrieved plan. Systems that create the PP rather than retrieve a ready-made one from the data-base are of the *generative process planning* (GPP) type. Since modification is of the order of complexity of generating a new PP, VPP systems are often of the *assistant* level of automation and the variant *vs.* generative characterization largely corresponds to the *assistant vs. expert* class. Thus far, no system is truly fully generative. The relationship between the levels of automation and the type of PP is schematically shown in Fig. 10.

The structured view of PP indicates that GPP stipulates the generation (or creation) of the PO while CAPP retrieves it. The generation of the PO is thus the crucial measure of ability to generate. A system is not a GPP one if it retrieves the PO, even though it may later provide some computerized facilities to modify and parametrize the PP. On the other hand, a GPP system may stop short of completing the PP, i.e. designing tools and parametrizing, but is still a GPP one. GT methods, including the ones that are not yet computerized, lend themselves to use by CAPP systems.

The nature of the technological knowledge of PP, even for the less complicated PPM, stipulates that *creativity* is essential to produce the initial stages of the PP - the PO. Hence, it was concluded by many researchers that a fully automatic PP system is not attainable and an interactive system for the generation of the PO is unavoidable. To some extent, recent applications of AI to PP hold some promise to modify this assessment.

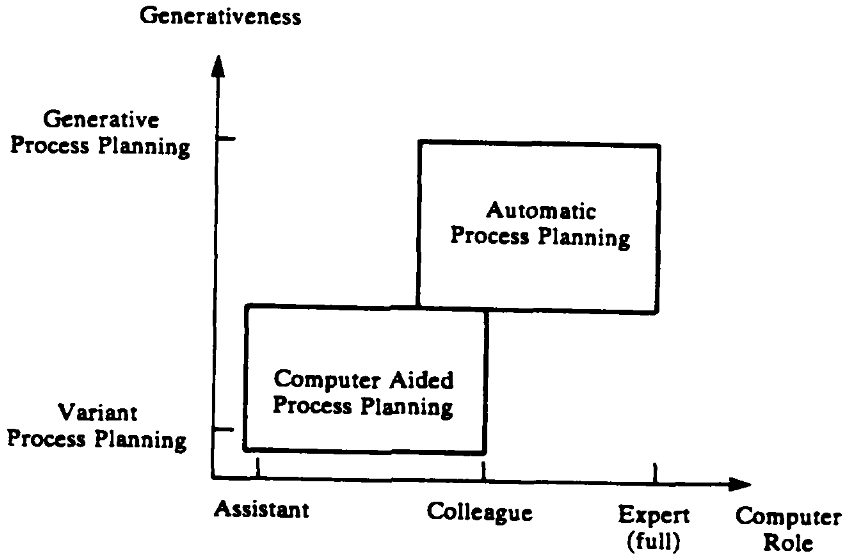

Figure 2-10. Levels of automation and method of creating the PP

2.2.2 Process Planning in Forming Processes

2.2.2.1 Scope of Forming Processes

In a forming process (group II in the classification in §.1.2) a solid body is subject to an external force and is irrevocably deformed. At the beginning of the deformation the workpiece is deformed ***elastically*** such that the strain is directly proportional to the stress. When relieved of external stress the body returns to its original dimensions. If external forces increase they may produce a combination of stresses that exceeds a certain ***yield limit*** and the body is permanently or ***plastically*** deformed. Actually, there is no complete recovery of the strain in an elastic deformation, and on the other hand, each irrevocable process exhibits a small degree of elasticity, but for reason of simplicity the behavior is idealized. Another instance of high idealization in forming is the assumption about rigid perfectly plastic bodies. The introduction of elasto-plastic behavior refines these idealizations. Idealizations prove useful for practical purposes as well as for scientific modeling.

The term *forming processes* (FPs) pertains to the entire range of processes in which the geometry of a solid metallic workpiece is altered under external forces without removal of material. The main properties that determine workpiece behavior under stress vary with material type, grain structure, temperature and rate, duration and history of the deformations. The

mathematical theory of plasticity attempts to formalize experimental observations of the macroscopic behavior of a plastically deformed body. Such treatment is found in comprehensive texts on plasticity e.g. [Hill], [JohnsMe], [Slate] and [Hosfo].

In spite of the remarkable progress in understanding the mechanism of deformation and development of new analytical tools in the last decades, complete mastery of the forming phenomenon has not yet been attained and the domain is still largely experience-based. Thus, prior to any analytical study of a particular FP, it is prudent to ask: "what are the influencing factors and how do they interact ?". The introduction of idealizations, which eventually enable analytical studies, is greatly enhanced by preliminary classification of the forming processes. There is no simple method of classification of FPs, but common measures are easily identified ([Slate]):

- Characterization by the homologous temperature: hot, warm, cold.
- A mechanical analysis point of view: state of stress of the workpiece (simple, complex, uniaxial, etc.).
- Type of stress involved: tensile, compressive, etc. .
- Characteristics of the plastically deformed zone: relative sizes and range; local (sheet forming) *vs.* comprehensive (bulk deformation processes).
- Strain rate class.
- Chip forming *vs.* chipless forming (viewing chip formation and separation as a forming phenomenon).

Several methods have been tried to combine the advantages of each of the measures above. Thomsen *et al.*[2] suggested a scheme that expands the *state of stress* classification in the deformed body. The four resulting groups are:

2. Thomsen, E.G., Yang, C.T. and Kobayashi, S. *Mechanics of Plastic Deformation in Metal Processing*, Table 1.1, p.4, Macmillan, New-York, 1965.

1. *Squeezing group:* the workpiece is subject to compressive stresses. Large changes in shape are produced, as in forging, extrusion, rolling, swaging and tube spinning. Many of these processes are hot worked.

2. *Drawing group:* the workpiece is principally subject to a tensile stress. Generally the deformation is smaller than in the "squeezing group" but large displacements are produced. The raw workpiece is in the form of bars, sheets or tubes. Processes produce primary changes in contour or relatively small changes in the smallest dimension of the stock material. Hot working is employed for the range of thicker stock materials. Processes in this group include: wire, bar and tube drawing, deep drawing, flow turning.

3. *Bending group:* the workpiece is subjected to couples, inducing stress gradient throughout the thickness. Change of shape is dominant, while change of thickness is mostly of secondary order. Sample processes include: flanging and brake-forming.

4. *Cutting group:* this group consists of two types of cutting: *chipless forming*, e.g. piercing, blanking, shearing, and *chip forming*, viz conventional and unconventional machining, e.g. turning, grinding, EDM, ECM, laser machining. In conformance with industrial practice only the first subgroup will henceforth be included in the range of FPs.

Surface finishing FPs such as shot and blow peening do not fit the above grouping and should form a special group.

[Lange] adopts the DIN 8582 std.[3] classification. According to this classification forming consists of five subgroups, as shown in Fig. 11.

Other significant classification practices produce largely similar groupings. A useful industrial division distinguishes between *sheet metal* forming and *bulk* or *massive* forming. From the physical sequence point of view, processes

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3. DIN 8582, "Fertigungsverfahren Umformen (Manufacturing Processes: Metal Forming)", 1st edition, 1971.

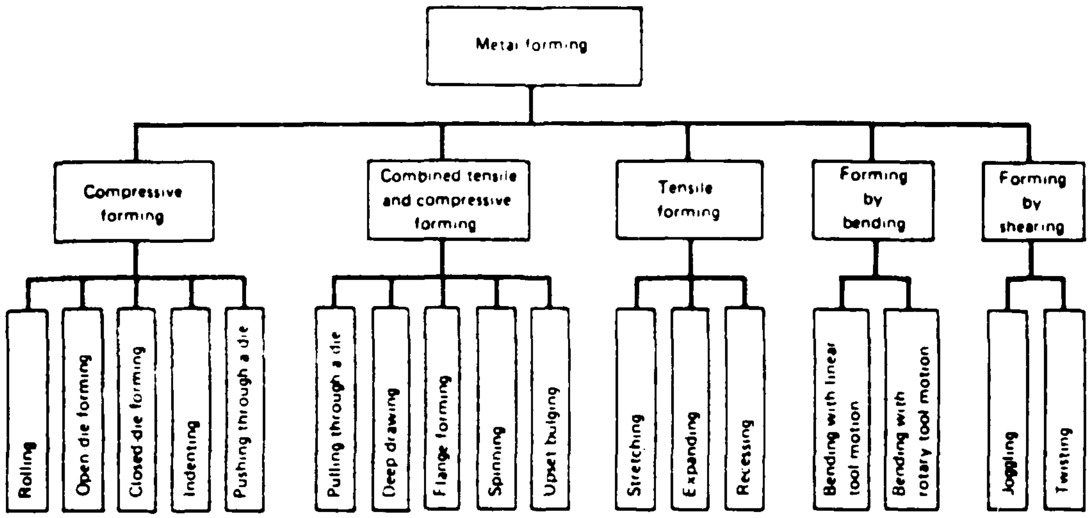


Figure 2-11. Metal forming subgroups in DIN 8582 ([Lange], Fig. 2.4)

may be classified into: *primary* and *secondary* ([AltanOG]). Primary processes contain the "squeezing group" and the non-forming processes, namely casting and powder metallurgy. This class is characterized by large strains with the metal being fluid or doughy. Secondary processes impart less subtle changes of form. Both small strain inducing FPs and machining are thus secondary processes. Further classification of secondary FPs by the type of deformation and relationship between processes is found useful for PP needs. The type of deformation is classified by the surface to volume ratio. The relationship between processes identifies *main* or *supplementary* processes. Supplementary processes complete or modify a main shape produced by a main process. Secondary FPs are grouped in Table 1.

In sheet metal forming, as opposed to massive FPs, the overall features of the resultant strain distribution are strikingly independent of properties of the particular materials. Values of failure strains do, however, depend upon material properties. This feature suggests that analysis of sheet-metal processes will be mainly geometric, while that of massive forming is more material oriented.

TABLE 2-1. Secondary forming processes

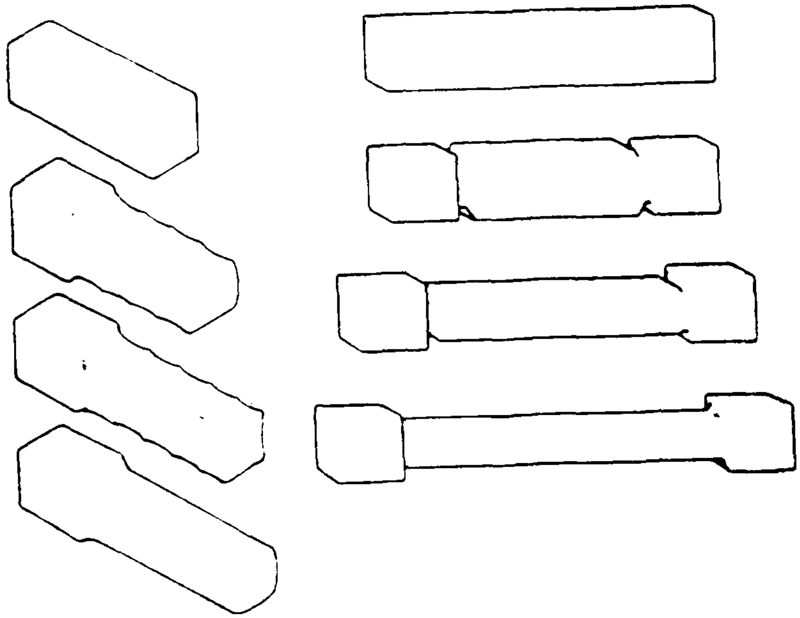
Secondary forming processes		
Deformation	**Class**	**Processes**
Low $\frac{\text{surface}}{\text{volume}}$ ratio	main	tube-drawing, shear forming, ironing,
	supplementary	nosing, reducing, tube sinking, tube expanding, surface finishing processes: shot and blow peening, burnishing.
High $\frac{\text{surface}}{\text{volume}}$ ratio	main	deep drawing, flow turning, bending, roll forming, punching, blanking,
	supplementary	dimpling (radius, cone, flange).

2.2.2.2 Part Manufacture by Forming Processes

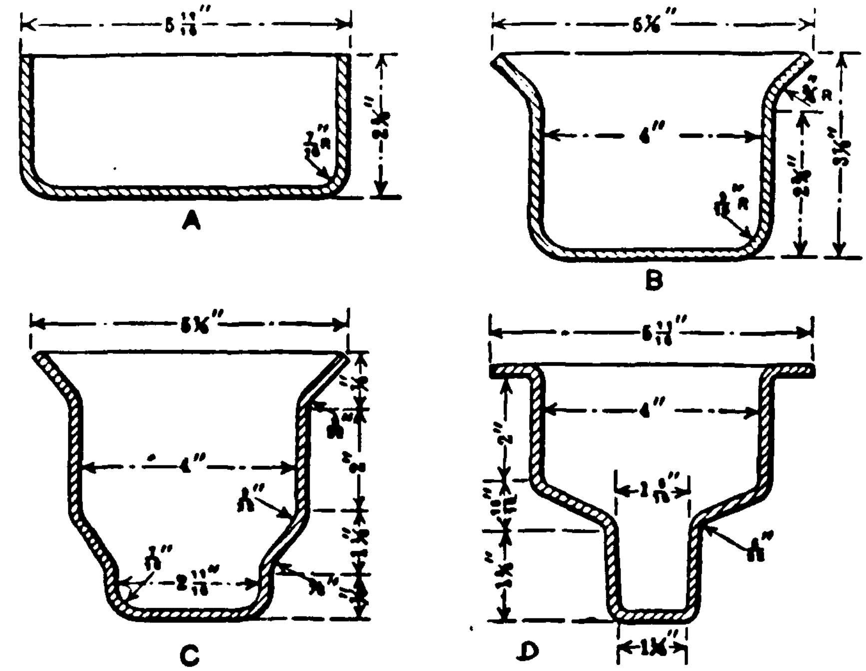
As an engineering domain, forming-only PP (PPF) corresponds to machining-only PP (PPM). In distinguishing between types of PPFs the above grouping of processes is helpful. The simplest PPF is the one built of "passes". Limit stresses and strains can be overcome by bringing the deformation about in several operations. If these operations are of the same process they are called *passes*. Passes may be performed on one machine, but unlike elements of a machining operation, a new set of tools is always required. Instances of sequences of forging and deep-drawing passes are shown in Fig. 12.

More complex manufacturing cases involve different processes, but of the same deformation group, e.g. massive forming, sheet-metal forming. Two instances of these "group FPs" are shown in Fig. 13.

The most complex forming-only manufacturing combines massive and secondary FPs. Naturally the sequence starts with a preform produced by a massive forming sub-process and complements the deformation by secondary processes, e.g. sheet-metal forming. An example is shown in Fig. 14. Nonetheless, some exceptions to the sequence of massive forming preceding sheet metal forming do exist. For example, ironing - a basically massive FP

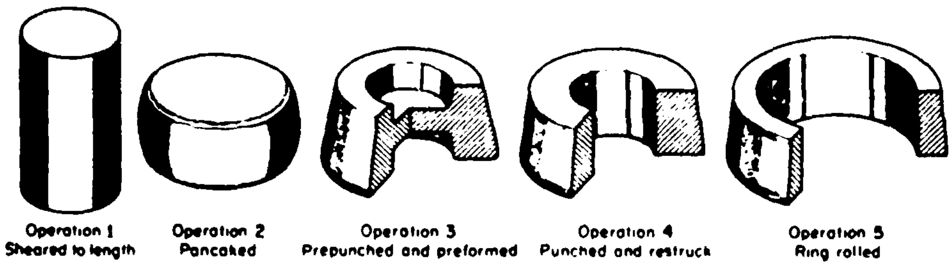


a. Forging PP ([Lyman5], Fig. 6, p.43)

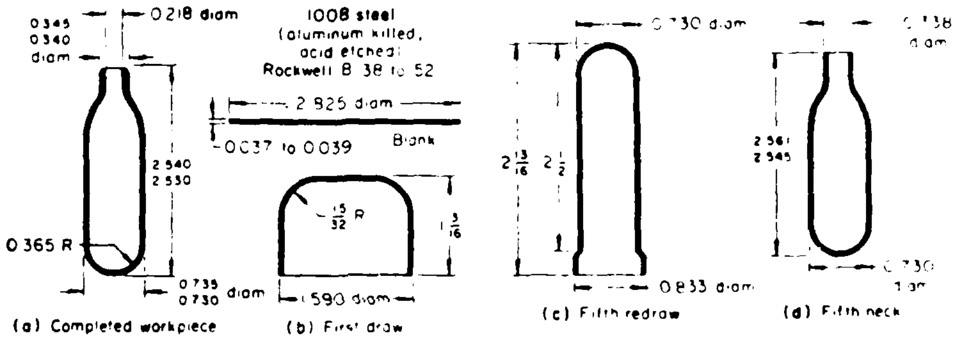


b. Deep-drawing PP ([Jones], Fig. 16, p. 622)

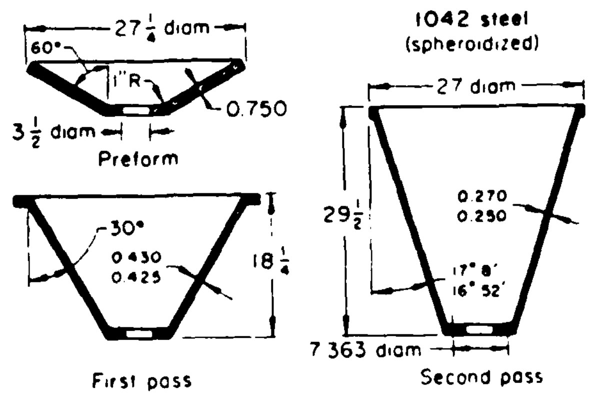
Figure 2-12. Forging and deep-drawing sequences (from [Lyman5] and [Jones])



a. **Bulk forming** **([Lyman5], Fig. 8, p. 107)**



b. **Deep-drawing (Fig. 68, p. 189)**



c. **Deep-drawing & spinning (Fig. 14, p. 205, [Lyman4])**

Figure 2-13. Sequences of operations of the same forming group

complements deep-drawing which is a sheet-metal FP.

2.2.2.3 Characteristics of Forming-only Process Planning

A PPF is much more difficult to create than a PPM. One reason is that, while feasibility of machining operations can be directly assessed and goodness-of-plan subsequently "safely" pursued, it is difficult to fully predict, before devising a PP, if a body is formable or not. After verifying producibility by a set of FPs, construction of the PPF, manual or automated, is more complicated than a typical PPM. This is due to knowledge gaps, much more prevalent in forming than in machining. One result is that a forming operation is characterized by *operation measures* that have to comply with prespecified *test measures* in order to meet feasibility. Nonetheless, the main component of feasibility in forming - formability - is not yet fully known or formalized for practical applications. A good feel for the limits of our knowledge of formability may be acquired from [Semia]. The role of feasibility is not the only difference between PPF and PPM, as is shown above. Other salient differences are discussed below.

Semantics of operations (see §.1.4) in PPFs is considerably different from that in PPM. *Qualifying operations* are contained by auxiliary operations; both facilitate next deformation. *Secondary operations* are practically nonexistent; the order of deformations and the strain path are of prime importance. The functions of the *supporting operations* remain basically the same. The structure of a PPF is context-dependent; it depends upon the form in which strain history is carried and preserved. Hot working preforms having their strain history annulled by heat-treatment, and being subject later to secondary deformations may allow division of operations into elements. Otherwise, when strain history is important, each forming pass, which may otherwise be considered an element, becomes an operation. In this instance only the level of operations does exist for that part of the PP.

Process parameters in a forming operation, though conceptually corresponding to machining parameters (speed, feed, depth-of-cut, tool geometry, coolant), are, in addition to being more complex, more process dependent. Process parameters may be *principal* or *secondary*. The former are independently determined, affect the feasibility of the operation and determine

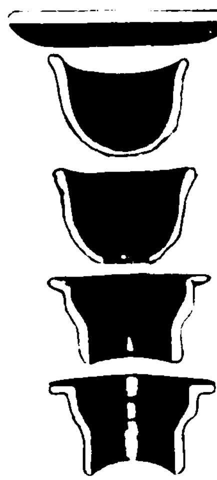


Figure 2-14. Bulk forming and subsequent sheet-metal forming PP ([Lange], Fig. 2.30)

the latter. Significant variables in FPs at large are given in Table 2.

Typical process parameters and process measures of sample forming processes are shown in Tables 3 and 4.

Other salient factors complicating PPF are:

- The end configuration is in itself part of the PP and affects feasibility, in particular in massive FPs. In machining, shifting from one standard stock material to another will only change some preparatory rough cutting operations.

- Some features of the end configuration cannot be independently specified. They are determined by other principal features and the strain path. For example: resultant thinning and strength of a drawn cup depend upon the strain path and cannot be arbitrarily specified.

- Strain path within each operation determines resulting mechanical properties and consequently feasibility.

- Accumulated strain history is a factor in determining resultant mechanical properties. Hence feasibility can be tested forwards only, i.e. from the first deformation on.

- Mechanical properties of the workpiece in the deformation zone are constantly changing during the operation.

TABLE 2-2. Significant variables of a forming process (extracted from [AltanLN], Table. 2, p. 81)

Process Variables	
Domain	**Variable**
Billet Material	constitutive relationship, forming limit curves, surface conditions, thermal-physical properties, initial conditions, relationship between changes of microstructure and constitutive equations and workability.
Deformation zone	Model of deformation, kinematics of metal flow, variation of stresses during deformation, heat generation and transfer.
Tooling	Geometry, surface conditions, material hardness, stiffness, accuracy.
Equipment	Speed, force, rigidity, accuracy.
Conditions at tool-material interface	Lubricant features, insulation and cooling at interface layer, application and removal of lubricant.
Product	Geometry, dimensional accuracy, surface finish, microstructure, metallurgical and mechanical properties.

- Feasibility is not attained with geometry, accuracy and minimum deformation force requirements being satisfied. The flow has also to be successfully completed, i.e. without defects developing.
- Knowledge gaps prevent parametrization from being "safe". One crucial area in which knowledge gaps are evident is the design of lubrication. For this reason, actual process parameters are often refined and adjusted after initial engineering specification through an experimental procedure.
- First operation always starts with a standard stock material.

2.2.3 Computer driven Process Planning in Forming Processes

2.2.3.1 Introduction

Pioneer research work in computer aided process planning of FPs originated ([Niebe]) at the same time ideas about automatic process planning in machining became consolidated ([Berra]). Niebel's system retrieved a basic process from a group technology (GT) data-base by matching a multi-disciplinary profile of the part. The profile was a 9-element vector that

TABLE 2-3. Salient process parameters for sample forming processes

Process	Process Parameters: Sample Principal Parameters	Sample Secondary Parameters
deep-drawing	Press and drawing method: punch force, blankholding force, type of drawing/redrawing: e.g. tapered, hemispherical, reverse-redrawing, etc. Sheet material: forming limit curve, forming limit diagram, planar anisotropy and normal anisotropy, Geometry: depth of cup and wall-thickness ratios, and die and punch rounding ratios.	Lubricant: sensitivity, stability, Tooling: clearance, stiffness, type of die curvature, Blank: surface condition, concentricity, Press: ram speed, blank-holding method, frame stiffness.
Closed die forging	Geometry: size and weight of forging, degree of deformation, web thickness and width, fillet and corner radii, draft angle, Material: stress-strain relationship, temperature sensitivity, grain structure, planar and normal anisotropy, Equipment: type of press, size, energy and stroke limits, temperature: limit and uniformity, hydrostatic pressure.	Geometry: flash design, closeness of tolerance, for hot forging: prior strain history, Lubricant: sensitivity, stability, Tooling: die material, control of die temperature, Equipment: maximum ram speed, press stiffness.

TABLE 2-4. Salient forming feasibility measures

Process measures	
Process	Measure of feasibility
deep drawing	machine size sufficiency, ram force sufficiency, adequate number of strokes, draw ratio, redraw ratio, height ratio, punch-rounding to thickness ratio, die-rounding to thickness ratio, taper severity, relative height of ears.
closed die forging	machine sizes, ram force and energy sufficiency, draft angles and corner radii, forgability value assigned to material (determined by upsetting test and other tests ([AltanBBAH], §4).

included managerial features. The computerized GT retrieval was a natural extension of the trends prevalent at that time. GT classifications, for machining as well as for FPs, have thrived in the 60's, notably in the Germanies. Prominent systems include "Spies", "Gurevitch", "Walter" and "Auerswald" for closed and open die forging, "Puschman", "Aachen-Opitz" and "Salford" for sheet metal parts, "Stuttgart" for flow turning and "Malek" for foundry products. An inclusive survey of GT methods for FPs is given in [GallaKn]. [Lange] extensively incorporates GT systems in the design of forming processes.

So far, computer driven process planning of forming processes (CPPF) did not catch up with its machining counterpart. Gaps in the technological knowledge of FPs have substantially retarded CPPF research. Naturally, existing systems are scarce. To-date, CPPF as such, is still in its embrionic stages. It is rationalized that since analytical solutions are unattainable unless geometry and boundary conditions are very simple, PPF cannot be realized in most cases. Commercial packages exist only for a distinctly limited scope of PP activities for sheet-metal forming. They provide graphic substantiation of the operations but in essence are restricted to simple geometrical manipulations only. The rest of the CPPF effort and systems of either CAPP or GPP type are at the experimental prototype stage. Even so they are limited in every sense of applicability. This notwithstanding, many of the potential tools are already available or under development, and their incorporation into a CPPF system is a "hot" research topic.

To overcome the analytical inadequacies a major research effort has been recently launched to utilize the computer to *model* forming processes. Process modeling (PM) is concerned with formalizing operating conditions of the process, thereby extracting constitutive relationships of the unknown variables. The results of simulating the deformation through process models (PMs) provide a process-planner with the knowledge how to parametrize or assess feasibility of an operation. PM may thus be considered a step towards CPPF but not CPPF in itself. Anticipated incorporation of PMs, together with other potentially useful tools for CPPF are briefly examined in the following sections.

A concentrated effort in PM, mainly for forging, has been ongoing in Battelle's Labs., partly with the cooperation of the University of California, Berkeley, since the early 70s (many details summarized in [AkgerSA] and [Nagpa79]). This effort brought major advances in computer aided PM (CAPM), such as finite element modeling (FEM) tools for the analysis of deformations: ALPID and extensions ([Kobay85], [OhLA81], [WuO]). These activities steadily developing towards CPPF. Implementation of computer aided PM has already taken place in industrial design (automotive industry, [ArlinFSM]) and shell-like products ([TangOh85]). In these instances and others, still at the research stage, PM directly assists such PP activities like die design and lubrication. Significant progress in CPPF work has been achieved in the GT discipline by teams of the University of Birmingham that later moved to the University of Oxford ([BiswaKn76] and [DavisKn]), mainly in forging.

Developments in artificial intelligence (AI) and expert systems (ES) may support the knowledge of FPs with capabilities previously attributed to human beings only. Mechanisms employed in systems that generate a sequence of forming operations ("FORMNG", [Badaw], FORMEX, [SevenRA]), utilize rule-based systems and programming in logic.

In evaluating process planning of forming processes it is noticeable that some of the existing prospective tools have not yet been formalized into CPPF applications. These include the bulk of GT systems and some process models. Mechanization of a GT system for forming is bound to work and benefit in the same way it does for machining. Lately, Knight and Poly ([KnighPo]) extended two existing GT codes ("Spies", and a previous classification by

Knight which combines salient features of "Spies" and "Gurevitch" and is described in [Knigh]) to produce a 4-digit polycode ([PolyKn]) that is also a design aid too. The first digit of this code describes the material and the other three the shape. Thus far, the Knight-and-Poly's code is the only one known to be directly used for PP purposes. Concise surveys of GT for forming systems are found in [GallaKn] and [Ross].

2.2.3.2 Computer Aided Process Modeling

Process modeling (PM) comes to bridge the gap between contemporary analytical knowledge and PP needs. Analytical modeling of FPs provides better insight into the process but does not as yet offer accurate prediction of workpiece behavior. Industrial practice, as a result, has to rely on islands of empirical knowledge, formulated in an "expert"-like fashion. PM was initiated in 1977 by the American Society of Metals, and Computer Aided Process Modeling (CAPM) has become since then a central research topic in forming. The objective of a process model for a FP is to *assist* the process-planner in designing and evaluating a given operation:

a. establish kinematic relationships between the initial workpiece and the deformed one,

b. establish formability limits of the examined part,

c. predict required forces and stresses to execute the forming operation.

PM, as other models, studies simplified, idealized deformation conditions. Along with a particular class of idealizations, PMs are characterized by:

a. Method of modeling and grain size: micro *vs.* macro.

b. Experimental *vs.* analytical.

c. Modeling tools (simulate deformation graphically, interactive operation).

The method of modeling is related to the elements the model manipulates. In machining, fine-grain models, e.g. the "deck of cards" (Earnst and Merchant) and "slip-line field" (Lee and Shaffer in 1951 and Oxley's expansion in 1956) explain the deformation of a small particle being sheared. A macro machining model interrelates the required cutting force, workpiece material, machining parameters and tool geometry. PMs of FPs, unlike PM of machining where the role of machinability is unambiguous, have to define the types of relationships and then compute the localized strains. The strain data are then correlated

with the formability data (that corresponds to machinability data in machining) to determine the status of the deformation.

[BoerJ] distinguishes two modeling approaches to metal forming:

a. system approach,

b. mechanic-detailed approach.

The system approach assumes a set of governing relationships the deformation obeys. Methods that are mainly used in this category are identical to the ones in manual analysis of FPs: the *slab, upper bound, finite difference* and *slip line field theory* methods. In the mechanic-detailed group, various FEMs are utilized to simulate in more detail a given state of stresses of the deformed body. FEMs are inherently computer based: a large number of elements have to be created, each defined by a set of nonlinear equations.

PM provides a theoretical insight into the motion within the deformation zone. While it does not design new operations or generate new process outlines it does provide the technological knowledge to parametrize one operation and test if completion is defect-free. PM is a hot topic in recent CIRP, NAMRC, MTDR and various metal forming conferences. State-of-the-art surveys of CAPMs for massive forming processes are given in [AltanLN] and [LahotOA], and for sheet-metal forming in [DuncaSo] and [SubraNA]. The work done by Battelle's Labs. is described in [AltanOh]. Boer and Jovane ([BoerJ]), while presenting a general inclusive survey, bring in important work done in Europe.

Material properties are part of the input but may also be an output of PMs. An input to a PM assumes a certain *material model*. A material model is a constitutive relationship of the form:

$$\bar{\sigma} = \bar{\sigma}(\bar{\epsilon},\dot{\bar{\epsilon}},T,S,)$$

where T is the temperature and S is the structure of the material.

Material modeling is concerned with:

a. initial mechanical properties and state of stress,

b. stress-strain flow characteristics ("constitutive relationships"),

c. conditions at tool-workpiece interface,

d. final mechanical properties and state of stress.

However, no standard representation of material properties has yet been adopted and their representation in each PM is tailored to the particular system. In general, non-FEM PMs enable more diverse representation of

material properties, e.g. piece-wise linear stress-strain relationships and the use of tables.

2.2.3.3 Computer Driven Determination of PPF

Mathematical complexity and knowledge gaps have retarded the development of formalized PPF systems. Not only CPPF systems are extremely limited in number, but the massive thrust of formalizing CAPP systems in machining has not been matched in forming. None of the "traditional" forming GT systems has been computerized and incorporated into a CPP system. ICAM software projects, which targeted the formalization of sheet-metal FPs, have not produced working systems either. At best, some GT codes are currently being developed into PPF systems (Knight *et al.*, see [PolyKn], [DavisKn], [BariaKn]). Existing commercial CPPF systems do not take material properties into account, and should thus be rather considered to be computerized *aids* to PP. The viable CAPM activities have also, thus far, stopped short of being realized as CPPF. A significant evolution in CPPF, though, is currently taking place with the introduction of AI tools, mostly in the form of *expert systems.* Whereas in machining both intelligent and "conventional" generative process planning exist, intelligent CPPF systems are thus far the only "real" computer driven PP in forming systems. Recent research into intelligent process planning in forming processes is outlined in the following section.

2.2.3.4 Intelligent Generation of Process Plans

Viewing PP as a graph, one notes that a major feature of CPPF is that both the next node (workpiece specification) and the edge (the transforming operation) are *indeterminate.* This relationship is schematically described in Fig. 15. The arrows there designate the physical sequence. In addition, as pointed above, in spite of the analytical insight into patterns of metal flow gained by PM, the knowledge for PP is still expert-like, i.e. not procedural and given in the form of "islands of knowledge". These observations opened an extensive thrust to attain PP with AI tools, namely rule-based systems (RBSs). While a conventional PP program requires the explicit specification of the entire range of candidate PPs, RBSs enable one to define isolated modules that can be composed by generalized inference engines

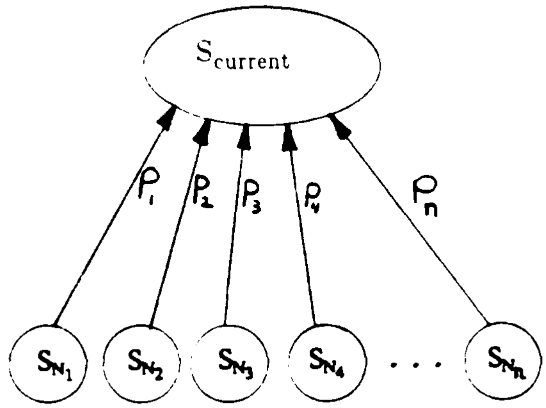
to full PPs. These systems have been inspired by the way a domain expert solves a problem, and try to emulate it. Hence their popular name: expert systems (ESs). The knowledge in ESs is not necessarily represented in the form of rules, though most ESs, including all PP systems, do adopt this representation. From the output point of view, PP systems are of the *plan synthesis* type, whereas most ESs are of the diagnosis (classification) type. Thus far all PP systems of the RBS type are still in the experimental prototype stage. A concerted effort by the CAM-I, though, is under way, to upgrade an experimental RBS for machining, "XPS", to a working industrial tool.

Once a final forgable preform is designed, the next stage of the PP is the design of the *blocker*. A blocker is related to a finished forging in the same way the rough machined workpiece is related to the finished workpiece. BID (Blocker Initial guess Design) is a prototype ES for the design of blockers, currently under development at Battelle's Labs. ([VemurBRA]). BID is a RBS, written in Prolog, currently applicable to 2D rib-web type forgings. Variables in the design of a blocker include: web thickness, fillet radius, corner radius, draft angle, rib width ([AltanBBAH]). The rules employed by BID relate dimensions of the examined feature of the finished forging, to the dimensions of the corresponding features in the blocker. The following is an instance of such a rule:

> **If** the forging is steel **then** fillet radius of the blocker is 1.5 times the fillet radius of the finish forging.

Being a 2D program, a set of supervisory rules manipulates the features of the finished forging sequentially. A predefined ratio between the volumes of the blocker and the finisher is preserved.

Preform design systems, of either GT or ES type, fall short of a full CPP practice. The circumscribing envelope is produced after human judgement is employed to analyze and classify the preform the part will be machined from. The stages in which the deformation will be completed are not elaborated upon. A real CPPF should, however, detail the manufacturing stages too, if the preform is produced in more than one pass. AI tools provide some means to overcome both obstacles: recognition procedures are expected to assign forgable features to the part and an RBS structure is expected to facilitate the multi-operation planning.



S - state of workpiece,
N - subscript, Next,
P - transforming process.

Figure 2-15. A portion of PP graph: neither the states nor the transforming operations are predetermined

The use of RBSs in CPPF has been initiated in Battelle Labs. in the early 80's, mainly for forging. It draws on preceding PM formalization. An ongoing effort is under way to broaden the scope of both applicable processes and workpiece features. CPPF systems of the RBS type are concerned with deriving the final forging and the design of blockers. Formalizing the design of blockers opens the way to multistage PP. The AFD (Automatic Forging Design) system ([TangOA]) modifies the design features to get a forgable preform. It has three modules:

a. Design Feature Extraction Unit. This module incorporates syntactic pattern recognition and classifies regions of the part to be designated as: rib, web, draft, corner of fillet.

b. Forging Geometry Design Unit. This module "adds material" to a sequence of features.

c. Forging Geometry Construction Unit: This module combines the above operations to construct the geometry of the final forging, or if this is unsuccessful, returns to the *b.* The design process thus becomes iterative.

3 RBSs are engaged in direct PP for various domains of forging processes. FORMNG ([Badaw] is a RBS that automatically designs the forging operations to cold-form an axisymmetric part. FORMNG is fed with the geometry of the required finished part, billet diameter, material specifications and friction conditions. It recognizes forgable features in the final part and splits the

geometry into deformation zones. The deformation zones are matched sequentially with the design rules in the data base. The program is written in FORTRAN and allows interactive input. FORMEX ([SevenRA]) is an RBS written in Prolog, currently under development. The applicable set of processes includes cold or warm forging operations: upsetting and backward and forward extrusion. The knowledge base of the system includes rules for each of the participating processes, "facts" about the forged materials and machines used, and rules for merging the operations.
An instance of a "process rule" is exemplified by the following upsetting rule:

> A bar, of length more than three times the bar diameter can be successfully upset in one blow, provided the diameter of the produced preform is not larger than one and one-half times the diameter of the bar.

Rules for sequencing the forming operations are much more complicated and defined in terms of specific geometries.

2.2.3.5 Workpiece Representation

A workpiece can be represented in an "objective" or in a "subjective" way. The objective way is represented by the engineering drawing. It combines the geometric description and the mechanical properties of the part. It is implemented in the *CAD* representation, while mechanical properties are given in an attached list. Principal methods of geometric modeling are outlined in [RaquiVo]. The *CAM* representation of the workpiece is the *interpretation* of the physical features w.r.t. a set of examined processes. The set of features has naturally to be compatible with the capabilities of the system. Hence, the CAM representation is both, process-dependent and system-dependent.

Existing CPPF systems either accept CAD representations and convert them later to CAM representation, or directly accept only the CAM representation. Since most of the parts manipulated by current CPPF systems are of 2D, both their representation and feature extraction procedures are simpler than CPPM systems that may employ 3D representations.

The input to GT systems that do not include intelligent feature extraction mechanisms, is a code. In Fig. 16 a coded part from [GokleDK81] is shown.

Sheet metal parts are mainly represented by their skeleton and thickness, in accordance with engineering drawing practice. The description of the sheet metal part in the AUTAP system is generated by a dialogue through the DETAIL-3 module ([EversAb]). The sheet-metal PP module of AUTAP; AUTAP-NC-STANZEN ([EversHo]) needs, however, an associate geometric description too. Since DETAIL-3 has no recognition capabilities it has to be directly fed with the additional, greatly overlapping description. The main description is made of the technical elements and the additional geometrical description.

The Prolog based RBSs represent a part as a set of *conjunctive* Prolog *facts*. Here, too, the representations may be CAD-like or of a CAM type. [SevenRA] uses a CAD representation, as shown in Fig. 17. [VemurBRA] accepts a CAM representation.

2.3 Machining a Part from a Preform

2.3.1 Design of Preforms and Deep-Drawn Preform Design Practice

Aside from thin sheet metal parts and some net-shape-forged parts, relatively few components can be produced to their finished geometry by forming processes. Thus, the great majority of multi-technology manufactures have the finished workpiece machined out of a *preform*. The notion *preform* is used typically to designate a product of forging and powder metallurgy out of which the final workpiece is machined. However, here its range is extended to all forming processes. The design of a preform, as of today, is rather an art than a science. It is process-dependent, requires great expertise and experience and is commonly thought of as not formalizable. Some typical preform designs and design stages for ring-rolling and closed-die forging processes are described in Fig. 18 (from [Lyman5] and [AltanBBAH]). The associated economic implications are extensively evaluated in the sources cited above.

Thumb rules for the design of forged preforms, based on decomposing the forged preform into predefined primitives, are elaborated in several forging reference books, e.g. [AltanBBAH]. Attempts to formalize and partially computerize the design of forgings date back to the early 70s ([AltanBBAH]

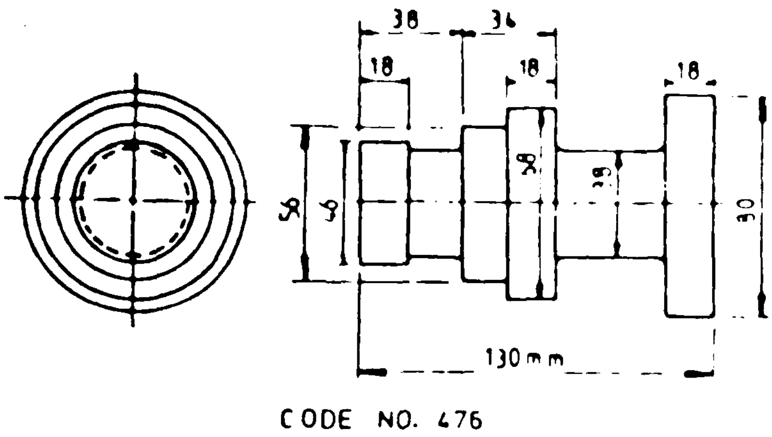
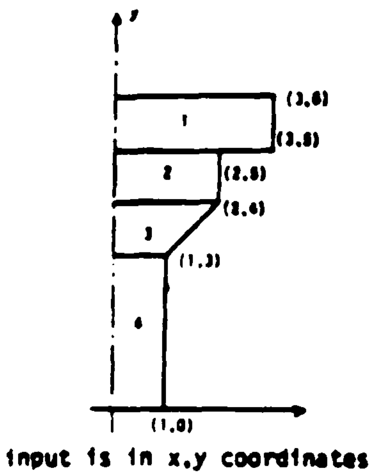


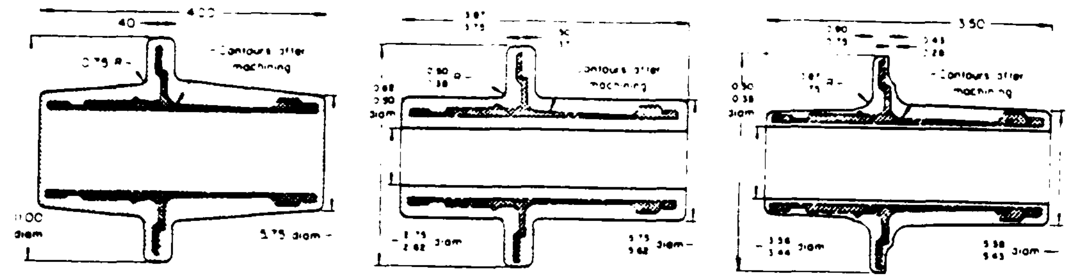
Figure 2-16. A coded shaft ([GokleDK81] Fig. 15a)



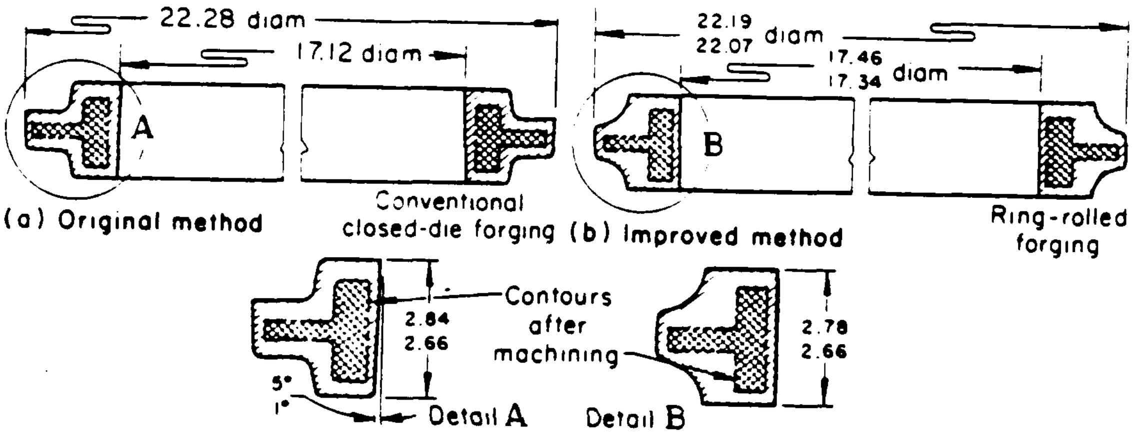

```
part(part1,[[3,6],[3,5],[2,5]
   ,[2,4],[1,3],[1,0]]).
```

a. part *b.* part representation.

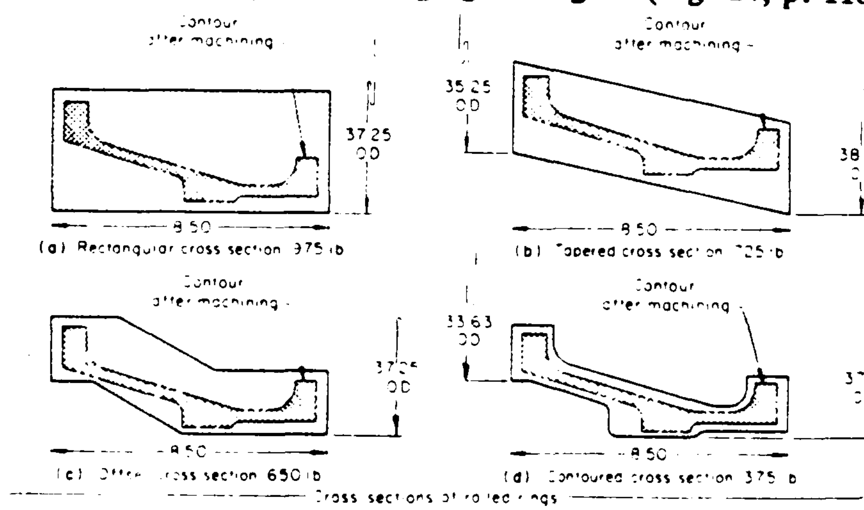
Figure 2-17. Part representation in FORMEX ([SevenRA], Fig. 11, 'input')



a-1: hammer forging *a-2*: upset forging *a-3*: contoured press forging.
a: Closed-die forging for a helicopter transmission shaft (Fig. 27, p. 66).



b: Closed-die and ring-rolled forging for a gear (Fig. 14, p. 110).



c: Ring-rolled preforms for a compressor-rotor spacer (Fig. 9, p. 125).

Figure 2-18. Different preforms for the same finished workpiece ([Lyman5])

and [BiswaKn]). Extensive research in computer aided design of forged preforms is conducted in Battelle Columbus Laboratories. Early programs from Battelle, developed in conjunction with the ICAM project, aimed at interactive capability, but more recent ones are directed towards automatic design. A sample automatic forging design from [TangOA] is shown in Fig. 19.

Workpieces produced by the technology of deep drawing and complementary machining are used in high-technology, small-batch parts, such as in the aerospace industry. In industrial practice, the deep-drawn preform can assume discrete wall-thickness values, e.g. increments of $\frac{1}{32}$inch in the range $\frac{1}{32}$ to 1 inch. In multi-pass drawing the resultant distribution of wall-thicknesses depends upon the strain path, i.e. the sequence of deep-drawing processes. Therefore, it is a common industrial practice to specify the finished drawn cup in terms of uniform *nominal* wall-thickness and minimum wall-thickness in particular zones.

The family of deep-drawing processes can produce a range of non-axisymmetric (cupping, redrawing, various hydroforming processes), non-monotonic (bulging, expanding, nosing, reducing, embossing) and non-uniform nominal wall-thickness (ironing) cups. However, axisymmetric monotonic cups of nominal uniform wall-thickness do constitute a significant portion of the overall realm of deep-drawings. Hence the automatic design of these preforms is by itself of real practical value.

2.3.2 Group Technology Type Design of Circumscription

Relatively simple design algorithms can be devised by a group technology (GT) type of circumscription. In GT-circumscription the preform is restricted to a predefined structure, e.g. straight vertical cup or a flanged vertical and tapered cup. In the generalized circumscription both the structure of the elements of the cup and their sizes have to be determined, and the task is of far greater complexity. Generalized circumscription by a uniform-wall-thickness deep-drawn cup, is shown in Fig. 20.

2.3.3 Related Computational Geometry Work

The particular circumscription problem ACDP is concerned with, or other constrained non-convex hull circumscriptions, did not attract thus far

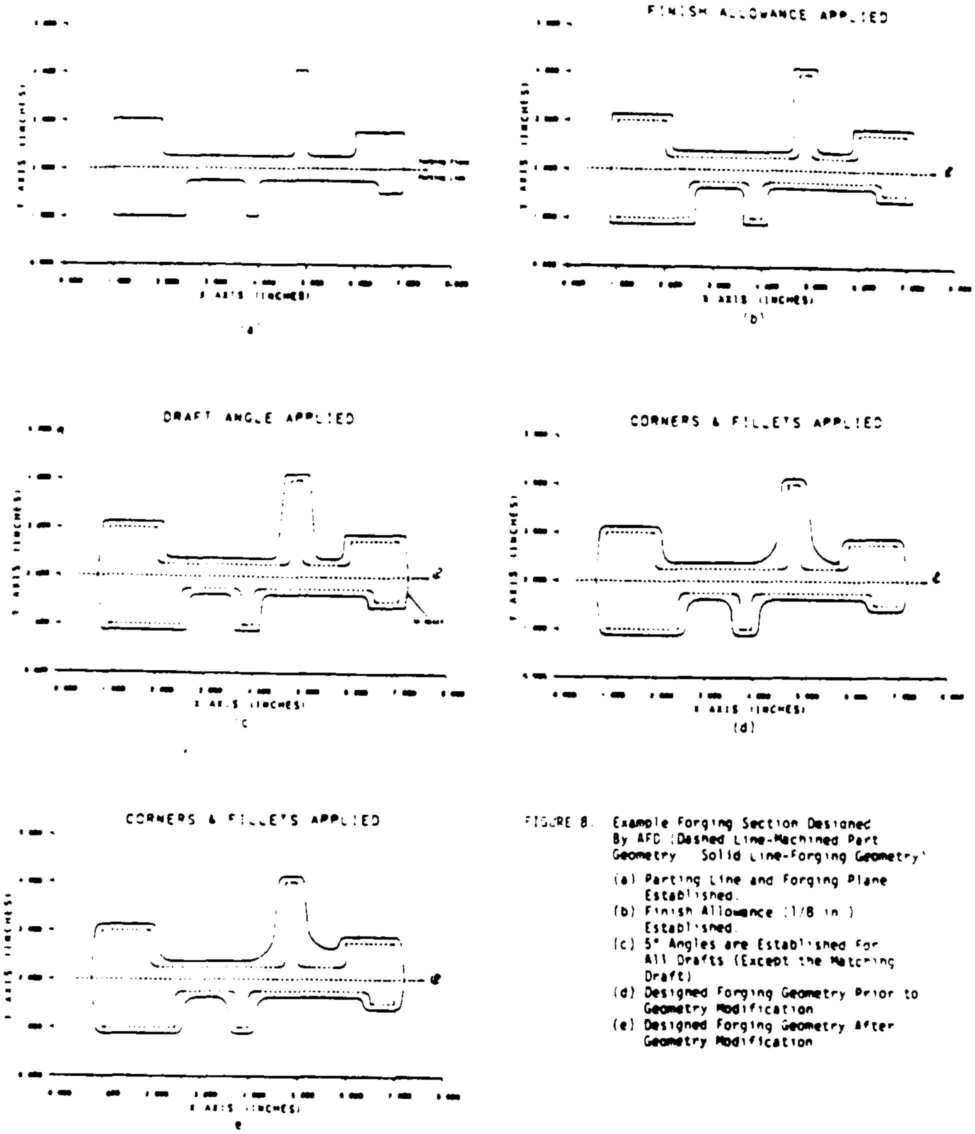
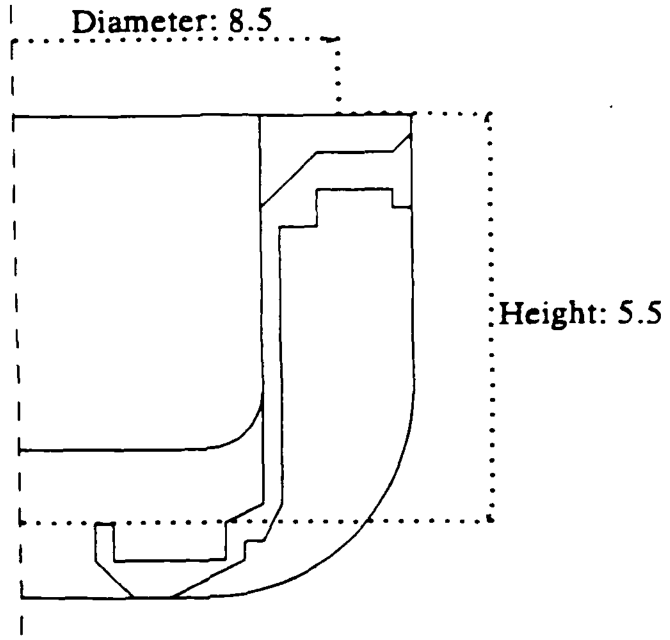
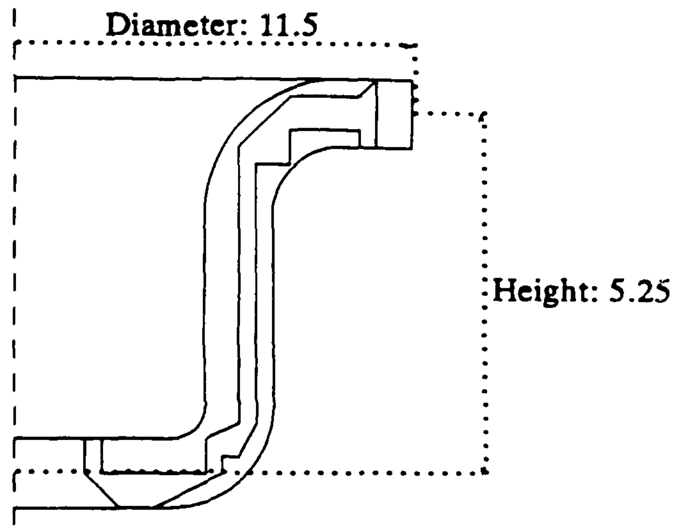


Figure 2-19. Steps in automatic section-of-forging design (from [TangOA], Fig. 8)



Uniform wall thickness: 2

a. Circumscription by straight vertical uniform wall-thickness cup.



Uniform wall thickness: 1

b. Circumscription by straight vertical and flanged uniform wall-thickness cup.

Figure 2-20. Group-technology-type of circumscription

much attention in computational geometry (CG). Decomposition of the task ACDP is after, yields CG algorithms for several basic issues. Some ACDP issues to which CG algorithms are applied are:

- *Point location*, achieved in $O(n\log n)$ preprocessing time and $O(\log n)$ query time, (e.g. [Kirkp]. Other references in [LeePr]). The method of detecting the number of intersections of a single-shot provides a result in $O(n)$ time.
- A general *polygon containment*, when the two polygons are of m and n sides, can be determined in $O(\, m^3n^3(m+n)\log(m+n)\,)$ time ([Chaze]).
- Determination of the *medial* was achieved in $O(n\log n)$ time, as a by-product of construction of the Voronoi diagram ([DudaHa]).
- *Linearization* is achieved in $O(n\,\mathrm{Radius}_{arc}/\mathrm{Tolerance})$ time. One arc can be approximated to a piecewise linear line (PLL) in $O(\mathrm{theta}\sqrt{\mathrm{Radius}_{arc}/(8\,\mathrm{Tolerance})})$ operations, where θ is the angle of the sector in radians, and Tolerance is the allowed distance between the arc and the approximating cord.
- *Intersection* of simple polygons of m and n vertices is achieved in $O(\,(m+n)\log(m+n)\,)$ time ([Shamo]).

Other relevant algorithms and related research are referenced throughout the detailed ACDP procedure.

As opposed to convex-hulls, monotonic polygons have drawn much more limited attention. As a result, algorithms for main convex-hull problems ([Yaglo]) are almost non-existent w.r.t. monotonic polygons. Results of significance, however, do include:

a: Simple polygons can be tested for monotonicity in $O(n)$ time ([PrepaSu]).

b: A n-sides monotonic polygon can be triangulated in $O(n)$ time ([PrepaSh]).

2.4 Problem Solving Techniques

2.4.1 Rule Based Systems and Automatic Reasoning

When *automated reasoning* is used to generate a plan it manipulates recursively the knowledge base to derive either new facts from the given ones or new subgoals from a sought goal. *Data-base search*, in contrast, *retrieves* facts from the initial data-base only. Expert consultation systems and related

plan generating systems are based on *solution-focused reasoning* ([Wos]), i.e. they have some a-priori knowledge about the frame of the outcoming plan. The "system" aspect of the rule-based system refers to a structure of:

- a data-base,
- a set of production rules,
- an inference machine,
- use interface.

The ***data-base*** is a set of *facts*. The set of production rules, together with the data-base, is sometimes called: knowledge base (KB). The *inference machine*, implemented through an interpreter, is a program which searches the KB for matching and instantiable terms and decides which rule to "fire" next. A ***production rule*** is an implicational form of a first order predicate calculus clause ([ChangLe]):

{ **if** { a conjunction of conditions } **then** { a set of consequences } }.

The above formulation is also written as:

$\{ A \rightarrow B \}$;

{ { antecedent } → { consequent } };

{ { conditions } → { action } }.

Here we shall use the goal-driven notation: { LHS ← RHS } which reads: "LHS is true if RHS is true". The first order predicate calculus, or predicate logic, manipulates *terms*. A term is either a constant, or a variable or a *function*. A function, or a *relationship*, is a symbol of the form: *relator*($Term_1, Term_2, .. Term_n$) where the *relator* is also called *functor*. *Horn clauses* ([Kowal]) are clauses containing, at most, one term LHS. They can represent: rules, facts and goals. A general *headed* Horn clause:

$$\{ B \leftarrow A_1 \wedge .. \wedge A_n. \}$$

is suitable for rule representation. *Facts* (assertions, unconditionally true terms) can be represented as headed clauses too: $\{ B \leftarrow . \}$.

Goals are *headless* clauses. A headless Horn clause is of the form:

$$\{ . \leftarrow B \} \text{ or } \{ (?) \leftarrow B \}.$$

Since the term B can be the consequent of a conjunction of terms a headless clause can be generalized to: $\{ (?) \leftarrow (B_1 \wedge B_2 \wedge .. \wedge B_n) \}$. The goal clause can thus be converted to a disjunction of terms using DeMorgan's law:

$$\{ \neg B_1 \vee \neg B_2 \vee .. \vee \neg B_n \equiv \neg (B_1 \wedge B_2 \wedge .. \wedge B_n) \}.$$

The last identity points to an important result which can be utilized in logic programming: a goal which is a conjunction of terms is true if none of the negations of its individual terms is true. Prolog, the logic-oriented programming language ([Clock], [Lloyd]), employs this mechanism and manipulate a unified representation of *goals*, *facts* and *rules*.

Rules can embed *frames* ([Nilss80]) and assume some *structuredness* ([Vere]). In a *structured predicate* the *relator* 'slot' is instantiated to relators of a particular semantic class (a unification that requires second order predicate calculus) and variables can be instantiated to generalized *frames*. Some expansions of rule-based systems relate the RHS to the LHS by some measure of confidence - *plausible reasoning* ([LatomLu]). In rule-based systems, of either deterministic or plausible type, in each primitive step *one* rule is applied. When more than one rule can be applied, a *conflict resolution* strategy selects the one to be applied.

Reasoning can be performed *forwards* or *backwards*. In forwards reasoning *action* means some manipulation of the data-base to produce new valid facts. *Backwards* or *goal-driven* reasoning evaluates the antecedent part of the rule until a data-base fact is matched. Backwards reasoning employs *direct* theorem-proving. It is assumed that if the goal is decomposed into a set of subgoals, and this set of subgoals is verified w.r.t. the data-base, then the goal is proved ([DavisKi], [Nilss80]). Initial and goal states are embedded into a *state-space graph*, which is searched according to a *search procedure*, specified by the control strategy. When performing a *depth-first* search it is preferable, in backwards reasoning, to create nodes only along the search path. One such class of search-techniques ("create and select" seems a more appropriate name) is *backtracking*. In backtracking, if a terminal node is reached and the goal not satisfied, the search returns back until an unsearched node can be created, or a failure is determined. Backtracking is employed in Prolog. Complexity of search depends on the number of data-items (rules and facts) in the working memory and their organization. Complexity can be brought down if access to the data items is organized in some data structure ([Deyi]) and if predicates are resolved by order of importance. *Structuredness* can make matching more efficient, save space in the working memory and reduce the number of different relators. Introductions to representing knowledge in rule form will be found in:

[Nilss80], [Kowal], [BarrF1], and therefore it will not be discussed here. Rule-based formulation emulates the predominant industrial practice, in which a deep-drawing specialist ("expert") provides the designer and the manufacturing engineer with information required to design efficiently the deep-drawing operations and to control and operate equipment.

2.4.2 Design and Plan Synthesis

Problem solving and *plan synthesis* or *plan formation* are largely overlapping notions. In [CohenFe] one can find the view that problem solving subsumes planning and design. In the context of this work, problem solving is taken to be the broad term that includes all types of solutions to questions, e.g. diagnosis, planning, prediction. A plan synthesis is thus the solution to a problem of the form: "transform an initial state into a final (goal) state, using a given knowledge base".

In most cases that human beings are engaged in and AI is concerned with, the goal is not directly retrievable from the data-base. A plan is typically developed over an incomplete knowledge base (KB), and may encounter huge number of possibilities, especially if variables are assigned values out of a continuous range. In most cases the plan has to it has to achieve a compromise among interacting sub-goals. Creation of possible alternatives and selection of one of them implies a *search* procedure. Hence, an efficient search method becomes the central issue in planning. Process planning tasks exemplify the huge, practically infinite, solution space. Ranges of variables specified by a process plan, e.g. speed of spindle, radius of curvature of die recess radius, are continuous and indeterminate. The huge search space suggests the introduction of a *hypothesis* as a practical way of planning. ***Deduction***, the other essential problem solving task, derives (***reasons***) new facts from a given set of prepositions (data-base).

Obviously, a successful plan is a *feasible* one, and it stipulates that each action is feasible. The output of the design can be considered as one such state. In view of the huge search spaces and absence of algorithms leading unequivocally to *optimal* plans, *feasibility* has become a measure of acceptance of plans. It is assumed in those planning procedures that *goodness* of the plans created is preserved.

Much of recent problem solving effort has been realized in the context of *expert systems* (ES). The ES is a problem solving mechanism, approach and system. Its product is a solution to a question. An ES attempts to obtain the solution in the same way a domain expert does. Stefic *et al.* [Stefi] distinguishes six classes of tasks ES perform: *interpretation, diagnosis, monitoring, prediction, planning* and *design*. Eventually, these ES tasks are problem-solving ones as well. Excluding *prediction*, the first three classes that follow draw on *classification*. The two latter ones are of the *synthesis* type. Synthesis creates something which is not stored in the data-base, whereas classification *retrieves* from the data-base. The majority of ESs, including those that have inaugurated the field, and those that have already matured beyond a research prototype, as MYCINE, DENDRAL, PROSPECTOR, HEARSAY I and II and ACRONYM, are of the classification type. Current concept of ES does contain, however, a wide spectrum of problem solving tasks. Several ESs turn out designs, e.g. Digital's XCON, or plans, e.g. IMACS, ISIS, PTRANS and GARI ([DescoLa]). However, in view of their classificational characteristics, the majority of ESs should be rather called *expert consultation systems*. Planning and design clearly do not belong to this class. Another related term - *program synthesis* - will be reserved for the automatic generation of computer programs (for example: PECOS, [Barst]).

It has been pointed out that problem solving can be viewed as search ([Simon]). By this token creating a plan and searching the nodes that constitute stages of the plan are rather overlapping notions. Hence search becomes a central theme in plan synthesis.

2.4.3 Search and Related Planning Strategies

Extremely *simple* problems may be solved by first building the entire search space and then scanning it. Simplicity is determined by the size of the KB and the expected *depth* of solution (the number of knowledge items taking part in the solution). The cause of simplicity is advanced by bounding the relevant KB to be searched and devising efficient search strategies. The first part is usually achieved by modularizing the KB. For example, it is useless to scan rules for medical diagnosis or, for this matter, rules for closed die forging if the desirable process plan is restricted to machining.

Fairly simple plans can be created by some kind of *uninformed* (blind) search. Uninformed search does not make use of any semantic knowledge to guide the search. The two basic uninformed search procedures are *breadth first* and *depth first.* Typically n items being manipulated to a d depth will produce a search space of $O(n^d)$ possible paths. Heuristic search methods are designed to make the search more efficient, i.e. to reduce the number of descendant nodes that branch out of each ancestor. They thus do not first create the entire search space and then scan it, but rather proceed along a potential solution path. This is done by *generating and testing* (G&T) intermediate nodes *along that path.*

The basic *nondeductive* heuristic search strategies employed in plan synthesis evolve from the depth-first search. In *backward chaining* a node that would achieve the goal is tested for satisfiability. If it is satisfied the search continues recursively until a plan that can transform the initial state into the goal state is found. Else, if a node cannot be satisfied, i.e the search fails, the program *backtracks* and a new candidate node is tested. The process goes on recursively. Outstanding variations on this approach are *problem reduction* and *means-ends analysis.* In *problem reduction* the goal is represented in an AND/OR tree and simultaneous backward chaining can thus take place. *Means-ends analysis* is concerned with improving the selection of the next candidate node to be tested for satisfiability. It does so on the basis of a seemingly sound premise that reducing the "distance" between the current node and the goal node brings the process closer to solution. The main means for reducing the solution space is the initial KB. It contains such valuable information as the:

- Hierarchy relationships among actions,
- Order relationships among actions,
- Interrelation of actions/states,

upon which the concrete heuristic search is often based.
Backtracking and other search methods are discussed in a textbook of heuristic search methods [Pearl].

In general, a plan synthesis strategy combines two "orthogonal" approaches: *exploration* and *evaluation.* An exploration-based strategy yields paths inexpensively but each path is highly susceptible to rejection. Employing an

expensive evaluation function makes the creation of each path more expensive but at the same time more promising. Naturally, the objective of a good plan synthesis is to minimize the overall "cost", which is composed of the costs of exploration and evaluation. Seeking to implement a "good" ***exploration - evaluation trade-off***, plan synthesis methods make use of the KB to produce an as-close-to-solution-as-possible first plan.

In *hierarchical planning*, in order to attain an initial good plan, intermediate stages for ***abstract plans*** are introduced. Every plan has some hierarchical structure, mainly due to the sequencing of operations. However, the term ***hierarchical*** in plan synthesis has a special meaning: it implies some ***abstract*** structure of plans. In this sense, a real, executable plan is a nonhierarchical plan. Various plan synthesis techniques that create an ***executable plan*** and then perform some kind of manipulation upon it are primarily nonhierarchical. STRIPS, HACKER and INTERPLAN apply these techniques. A major disadvantage of nonhierarchical planning is that it does not distinguish between critical and trivial operations. Therefore plans developed by nonhierarchical planning systems get bogged down in unimportant details. A nonhierarchical planning procedure to plan the journey between location **A** in city **a** to location **B** in city **b** with the help of conventional road maps, will issue, at each iteration, a full journey plan, to the last detail. One planning possibility is to start with the **a** city map, and find there a route from **A** to a main road (e.g. a state highway) that is expected to lead to a principal highway (e.g. interstate). Next step will then select one of the principal highways that intersects the main road and stretches to the vicinity of **b**. This simplified procedure will end when the city map of **b** is reached and the path from a main road entering that map to **B** is selected.

In *hierarchical planning* all the top levels are *unexecutable.* Only the bottom one is a real plan. Each level is *refined* into a less abstract one, until an executable plan is reached. GPS, ABSTRIPS and NOAH employ various hierarchical planning techniques. One way of implementing hierarchical planning to plan the journey of the above example is to maintain the upper layers as lists of points in the sought route. In the first level of abstraction, $1_{junction}$ between **a** and **b** would be chosen. Next, $2_{junction}$ that lies between $1_{junction}$ and **a** would be chosen. And so on, until a the list of junctions created

constitutes a valid and an unambiguous route. As for computational efficiency, nonhierarchical planning saves abstract planning levels but is bound to run into large error-prone searches.

Skeletal and *opportunistic* planning embark on aspects of human planning not being addressed by hierarchical and nonhierarchical planning. *Skeletal planning* ([FriedIw]) retrieves, or creates, an *outline* of a plan that consists of generalized steps. The generalized steps are liable to be instantiated by a range of plans. Any plan that first produces an outline and then fills in the details, demonstrates some elements of skeletal planning. Group-technology (GT) based process planning is one common manufacturing application of skeletal planning. Still, one has to be careful not to mix *planning in phases* with skeletal planning. A machining application of *planning in phases* has the sequence of machining processes and surfaces being determined in the first phase, and computes the detailed machining parameters in the second. It is presumed in *planning in phases*, that determination of the detailed parameters does not change the *feasibility status* of the plan. EXCAP adopts this mode of planning.
In a journey planning task one would first set up an *outline*. The first operation of that outline may state: "take the closest non-one-way road from **source** that runs southward and continue with it until you hit a road coded by two-digits". In our journey problem **source** is instantiated to "**A** in city **a**".

Opportunistic planning is a strategy of building the overall plan piecewise. Parts of the plan, - *islands*, are being developed separately and put together as *opportunities* present themselves. DEVISER ([Verc83]), for example, expands unsatisfied subgoals in parallel until they can be joined, starting each search from an updated *window*. A typical portion of an opportunistic journey planning will start with finding the principal highway, e.g. an interstate road on which most of the journey would take place, and look for the junction nearest to **A** in city **a**.

Phased planning may be viewed as one extreme form of the *least commitment strategy*. This strategy stipulates that the less important but more detailed planning steps will be taken under sufficient belief (evidence) that they will not be later abandoned. The more detailed phases of nonhierarchical and skeletal planning, and the executive level of hierarchical planning will be

attempted following a *least commitment strategy*.
In road map planning, an absolute commitment to phased hierarchical plan can be a faulty strategy. For example, if an intermediate milestone is not going to be changed even if it leads to a dead-end road then the plan synthesis procedure may falsely lead to the conclusion that the journey is impossible.

The human planning practice of using a plan as a basis for improvement is emulated in the *plan improvement* branch of planning strategies. As with the least commitment strategies, a plan improvement program may be incorporated in a plan based on any of the aforementioned main strategies. Thus far however, it has been used only by programs that produce the initial *tentative plans*, e.g. DCOMP, ([Sacer75]). In DCOMP the plan improvement mechanism (called there: *plan amendment*) is invoked when the tentative plan fails. An issue with plan improvement is: how drastic are the alterations that can be imparted. Note that the term *plan refinement* is usually reserved for instantiating *skeletal plans* and should thus not be considered a part of a plan improvement strategy. G&TR, as will be shown below, basically implements a plan improvement strategy.

2.4.4 Generate and Test

Generate and test (*G&T*) is the core mechanism of *nondeductive* problem solving. It essentially implies that the information is incomplete and some *guessing* or *plausible reasoning* has to be made. It is as if whenever current knowledge is not adequate to *deduce* a plan, another piece of knowledge that "shortcuts" the path to the solution is introduced. Having hypothesis procedures legally embedded in the KB renders the creation of a plan a *reasoning* task. The basic idea of *G&T* is fairly simple: "*Hypothesize* about a solution and *test* it. If the test succeeds, report and *stop*, else *generate* next hypothesis and continue recursively". As with other guessing methods, *G&T* has to recognize faulty guesses and derive better ones from them. In the early 70's a differentiation was made between *G&T* and *heuristic search* ([BarrF1]). It was then held that *G&T* refers to the generation and test of states of the search space, while heuristic search controls the order in which the states are generated. Later on, Newell and Simon collapsed the two into one ([BarrF1]). The relationship between heuristic search and planning presumes that *G&T* may employ articulated hypothesis generation methods

while heuristic search determines the path in which they are generated.

Modifying Newell and Simon ([NewelSi]) formulation, a recursive *G&T* scheme is:

procedure *G&T* (recursive):

if *generatable*($P_{current}$) **then**
{ *generate*($P_{current}$),
test($P_{current}$),
if *succeed*(*test*($P_{current}$)) **then** { *report*($P_{current}$) $\wedge$ *stop* }
else *G&T*(P_{next}) }
else { *stop* $\wedge$ *report*("No solution") }.

From procedure G&T one can see that a solution will be found if it does exist and if the *generate* procedure can generate it, and sufficient time (space) is allowed for the search. Rigorous, but domain-dependent, formulations are found in literature, e.g. scene-analysis G&T, ([Mulga]). If the *generatable* relationship is an intrinsic procedure of *generate*, which is usually the case in RBS, a failure to generate would invoke the termination of the program.

Expert systems have used *G&T* from the early days of the evolution of the field. Notable examples include DENDRAL, VISION ([WesleHa]) and HEARSAY-I and HEARSAY-II.

The *hypothesis* part of the *G&T* is studied in several related disciplines. *Philosophy* is concerned with hypothesis in the context of *logic-of-discovery*. The relationship between *observational* (or, as it is otherwise known: experimental, empirical) and *theoretical* statements, or *propositions* ([Hajek]) is predicated on:

- Conditions that make a theoretical statement significant with respect to a given observational evidence,
- Methods of assessing predictability power of a theoretical statement.

Mathematical-logic examines the generation of hypotheses as a part of *logic of induction*. Sample questions here are ([Hajek]):

- In what languages are observational and theoretical statements formalizable ?
- What inference rules can bridge the gap between observational and

theoretical statements ?

– What is the rationale of determining the truth of a theoretical statement based on given observational data ?

In deductive logic, a method for obtaining falsehood-preserving inference rules was developed ([Morgan]). A set of falsehood-preserving inference rules can be used to generate *all* hypotheses from which a given expression can be deduced. This method reversely proves the correctness of the hypothesis. *Statistics* evaluates the probability of accepting a *zero hypothesis* against an *alternative hypothesis*, but is not concerned with formulating these hypotheses.

Primary task of the hypothesis-generator is to create *all* workable hypotheses. Varying degrees of incompleteness of the KB result in a diversity of methods of producing hypotheses and testing them. The task is complicated while probabilistic/fuzzy data is fed, or if the possibility of erroneous data exists. *G&T* is suitable for scene analysis systems. The task there is basically of the *classification* type. Some a-priori knowledge about the range of possible objects and their features enables the system to come with "educated guesses" about the scene. Deductive recognition in such cases, is impossible because of complexity.

3. TECHNOLOGICAL KNOWLEDGE of DEEP-DRAWING

Nomenclature

Notations used in cup drawing and stretching are shown in Fig. 1 and 2, and stresses of a plane element in Fig. 3

Subscripts and **superscripts** (designating a general x):

x_0 - initial, at the beginning of the operation.

x_{cur} - current.

x_C - pertains to compressive state.

x_f - final, at the end of the operation.

$x_{1\,2\,3}$ - principal directions for stress/strain (Fig. 3).

$x_{x\,y\,z}$ - axes in Cartesian system.

$x_{r\,h\,\phi}$ - coordinates in cylindrical system (Fig. 3).

x_{max}, x_{min} - extremal values of x.

$\bar{x}$ - effective, representative, or: mean average.

$\dot{x}$ - derivative (default: w.r.t. time).

x_T - tensile stress regime.

x_U - pertains to ultimate strength, onset of instability.

$x_{(f),(w),(b)}$ - flange, wall, bottom, - denoting regions of the cup.

Symbols and terms:

$X\uparrow$ - the value of X goes up.

$X\downarrow$ - the value of X goes down.

α - die-bend angle, determines conicity.

β : stress ratio: $\sigma_{wall(\epsilon_y=0)} / \sigma_{flange(\epsilon_z=0)}$.

ΔR - Normal Anisotropy ($\Delta R = \epsilon_t / \epsilon_{length}$).

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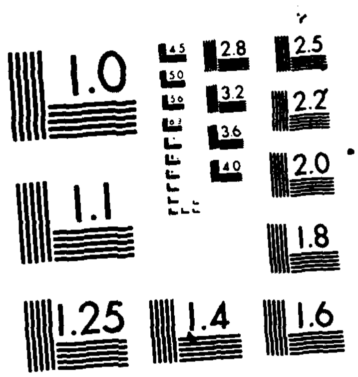

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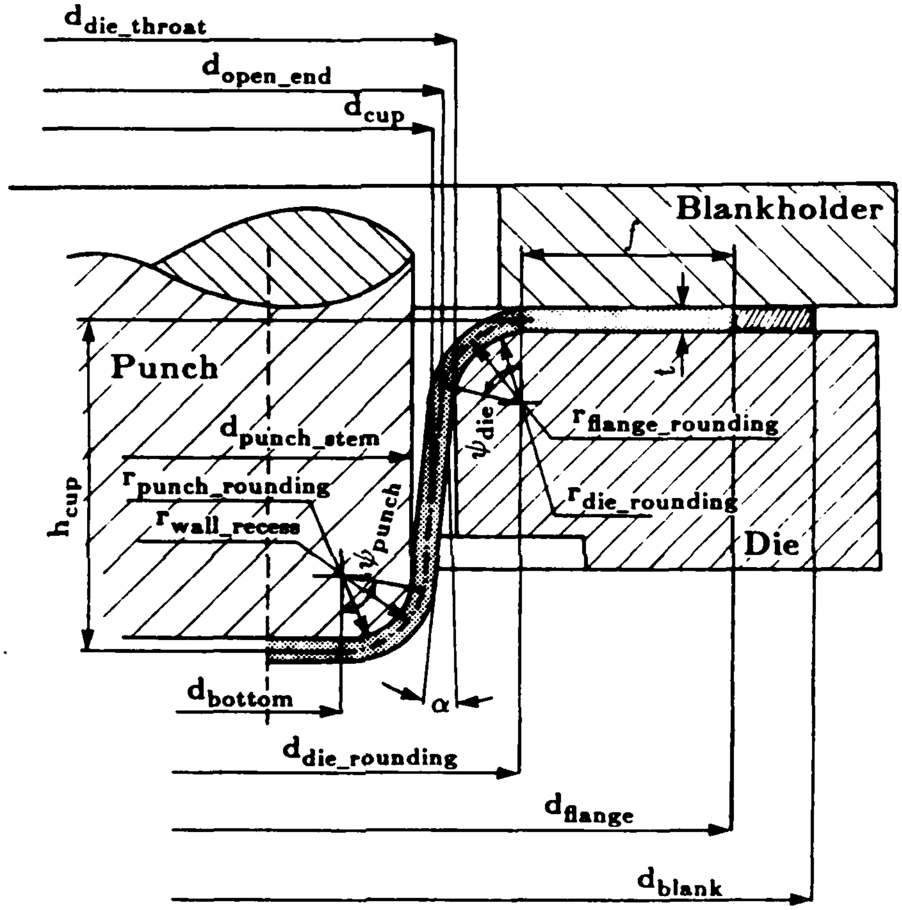

Figure 3-1. Tools and regions in cup-drawing

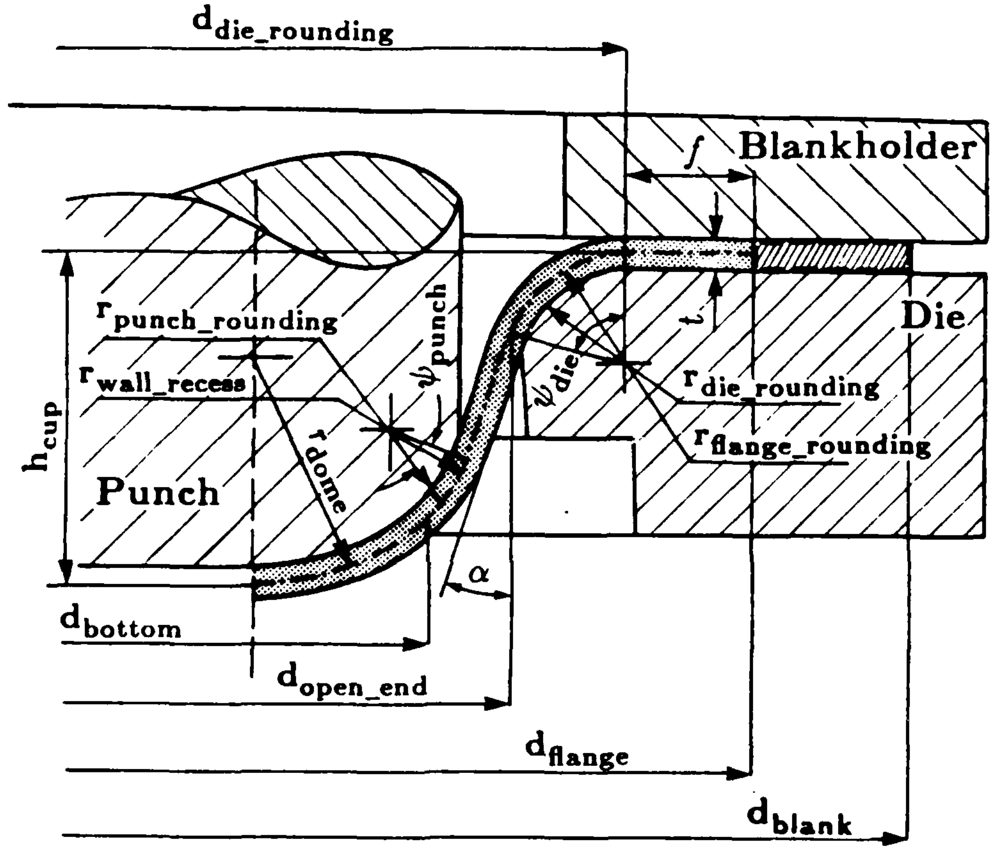

Figure 3-2. Tools and regions in stretching

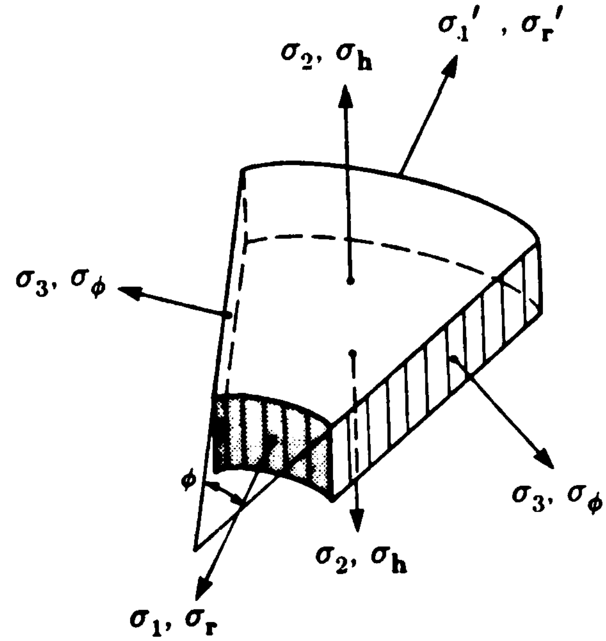

Figure 3-3. A plane element of a circular plate

ϵ - strain. $\bar{\epsilon}$ - effective strain. $\dot{\epsilon}$ - strain rate.

η - efficiency of work: $\text{Work}_{\text{ideal}} / \text{Work}_{\text{actual}}$.

θ - an angle of a small element in plane.

μ - friction coefficient.

σ - axial stress (+ tensile, — compressive).

$\bar{\sigma}$ - representative stress (root mean square of sum of shear stresses).

$\bar{\sigma} - \bar{\epsilon}$ - Stress-Strain relationship.

τ - shear stress.

ϕ - diameter.

ψ_i - angles in redrawing.

A_i - general constants, explained in the context they appear.

B - general constant, or: coefficient (as in stress strain relationships, e.g. $\sigma = B\bar{\epsilon}^n$).

b - the slope of the true-stress - natural-strain curve (approximate in exponential curves).

bottom - the downmost element in cup (see Fig. 1).

C - coefficient (default: in stress — strain-rate relationships, e.g. $\sigma = C\dot{\epsilon}^m$). or: subscript denoting: compressive.

C-P - Computation Parameter.

d - Diameter.

die impact line - the line separating the zone in which drawing is the main mode of deformation from the one in which stretching prevails (see Fig. 14).

D - Draw Ratio: $d_{\text{blank}} / d_{\text{final-cup}}$.

D Rule - Design Rule.

DR - Die-rounding.

DRR - Die-rounding Radius Ratio: $d_{\text{die throat}} / r_{\text{die rounding}}$.

DRT - Die-rounding to Thickness Ratio: $r_{\text{die rounding}} / t$.

e - nominal ("engineering") strain.

E - Young's modulus.

E_{buckling} - buckling modulus: $E_{\text{buckling}} = 4\,E\,b \,/\, \left(\sqrt{E} + \sqrt{b}\right)^2$.

edge - the part of the flange that may be supported by a blankholder.

f - width of the edge.

flange - the topmost element in a cup if it is perpendicular to the axis of symmetry.

F - force.

FLC, FLD - Forming Limit Curve, Forming Limit Diagram.

FTR - Flange Wall-Thickness Ratio: t_{flange} / t.

h - height.

HR - Height to diameter Ratio in a cup: h_{cup} / d_{cup}.

k - shear strength.

K, K_i - coefficients.

L - a prefix for "Limiting":

LD - Limiting D.

LDRR - Limiting DRR (minimum and maximum values).

LDRT - Limiting DRT (minimum and maximum values).

LFTR - Limiting FTR

LHR - Limiting HR.

LPRR - Limiting PRR (minimum and maximum values).

LPRT - Limiting PRT (minimum and maximum values).

LRD - Limiting RD.

LRR - Limiting RR.

LSR - Limiting SR.

LTap - Limiting Tap.

LTR - Limiting TR.

LTT - Limiting TT.

m - strain rate exponent in the stress - strain-rate function: $\sigma = C\dot{\epsilon}^m$.

or: Hill's experimental non-quadratic exponent in the yield criterion. For in-plane isotropic, plane stress conditions, with $\sigma_3 = 0$:

$$|\sigma_1 + \sigma_2|^m + (1+2R)|\sigma_1 - \sigma_2|^m = 2(1+R)\,\sigma_U{}^m.$$

or: Tresca yield criterion modified constant, default: $m = 1.1$.

n - strain exponent in the stress - strain relationship: $\sigma = B\epsilon^n$ or: $\sigma = \sigma_0 + B\epsilon^n$.

P - Punch force.

p - external pressure.

PR - Punch-rounding.

PRR - Punch-stem to Punch-profile Radius ratio: $d_{punch\ stem} / r_{punch\ rounding}$.

PRT - Punch-profile Radius to Thickness Ratio: $r_{punch\ rounding} / t$.

r - radius.

$\dot{r}$ - radius of a sphere.

R - planar anisotropy: $R = \epsilon_{width} / \epsilon_{length}$. $\overline{R} = (R_{0^\circ} - 2R_{45^\circ} + R_{90^\circ})/4$.

R Rule - Rectify Rule.

RBS - Rule-Based System.

RD - Redrawing Ratio: $d_{stage_i} / d_{stage_{i+1}}$.

RHS - Right Hand Side.

RR - Reduction: $(d_{stage_i} - d_{stage_{i+1}}) / d_{stage_i}$.

SR - Height Ratio of a Spherical Element: $h_{spherical\ element} / d_{dome}$.

T - subscript denoting: tensile.

t - Wall Thickness. Default: nominal wall thickness.

T-P - Test Parameter.

T Rule - Test Rule.

Tap - Severity of drawing tapered cups (Conicity Severity).
Defined as: $Tap = LHR_{vertical\ cup} / LHR_{tapered\ cup}$

TR - Wall Thickness Ratio: $t_{deformed\ zone} / d_{deformed\ zone}$.
or: individual T Rule.

TT - Wall Thickness Thinning, defined as: e_t.

U - as a subscript, denotes: ultimate (strength), onset of instability.

UE - ultimate natural strain a particle in $cup_{current}$ undergoes, w.r.t. its initial shape, as a part of the blank: $\epsilon_{U_{Max}}$.

W - work. w - work per unit volume.

wall - the region between the flange and bottom in a cup.

Y - yield strength.

3.1 Introduction

Deep-drawing, with *pressworking*, *stamping* and *die-forming* being commonly used synonyms, is an experience-based technology. A natural procession of investigation starts with an experimental study from which analytical models can be developed. "Know-how" has been accumulated, largely by trial & error, since the process was introduced in the 18-th century, though a massive thrust to understand it started only in the 1920's. Early workers[1] measured changes in thickness undergone by a uniformly thin blank

when drawn into a cup and tried to predict the drawing force. A comprehensive experimental and analytical investigation was carried out by S.Y. Chung and H.W. Swift at the University of Sheffield ([ChungSE]) in 1950, and this set the course for much of the subsequent research. Among other experiments, Chung and Swift drew 4 inch diameter cups of varying blank sizes, thicknesses, recess radii, materials and operating conditions, with each cup undergoing a total of 500 to 900 measurements. The analytical treatment utilized some of Hill's ([Hill]) predictions as applied to the strains developing in radial drawing. Earlier experimental investigations were mainly concerned with isolated aspects of deep-drawing of the radial drawing regime only. The small scale on which they were conducted afforded only descriptive results ([ChungSA]). Along these lines, Eksergian, Siebel, Crane and Sachs (see above) investigated punch loads, and Fukui (1938) and Swift (1939) attempted to measure and model thickness changes. Helpful interpretations of Chung and Swift's investigations are found in the works of [Hesse] and [Willi].

A great deal of effort has been put into both experimental characterization and analytical modeling since Chung and Swift's work. However, the basic metal flow pattern is neither sufficiently known nor mathematically formalized. Also, precise behavior and quantitative values of principal process variable such as *friction* at the tool-workpiece interface, *heat generation* in material, lubricant and tools, *heat transfer* during the deformation and initial *material properties* and their change during the deformation are difficult to measure, analyze and predict. Analytical results are obtainable only if considerable

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1. Eksergian, G.L., "The Plastic Behavior of Metals in Drawing", in *ASME Transactions*, vol. 48, p. 609, 1926.

   Sachs, G., "New Research on the Drawing of Cylindrical Shells", in *Proc. Inst Automobile Eng.*, vol. 29, p. 588, 1934-5.

   Crane, E.V., *Plastic Working of Metals*, John Wiley and Sons, N.Y., 1931.

   Fukui, S., "Researches on the Deep-Drawing Process", *Scientific papers of the Inst. of Phys. and Chemical Research*, no. 849, p. 1422, 1938.

   Siebel, in 1929 and Swift in 1939, see references in [ChungSA].

idealizations are introduced.

Analytical treatments of deep-drawing follow well-known idealized plasticity methods, e.g. slab analysis ([JohnsMe], [Slate]), homogeneous work ([Hosfo], [JohnsMe]), slip-line field analysis for ironing ([JohnsMe]), upper-bound techniques ([Avitz77]), and finite element methods (Levy, Anderson and Kobayashi[2]). Idealizations, while providing a better understanding of the process, are only applicable for limited number of variables, and not always do they provide useful solutions. Thus, empirical rules are used for cases where theoretical predictions do not satisfactorily agree with experimental evidence. The technological knowledge of deep-drawing is constantly being updated, especially w.r.t. forming limits. Also the overall division between theoretical and empirical knowledge is not static. But, in spite of the considerable progress in understanding metal-flow in deep-drawing, constructive process design handbooks have utilized thus far metal-flow analysis only to a limited extent. Obviously, empiricism is conspicuous in present designs of complex drawing processes for parts.

The experimental verification of deep-drawing is aided by tests simulating the forming conditions ([Meule], [HobbsL3]) and by analysis of observations in large number of drawn cups ([Hosfo], [HobbsL9]). In such a way *formability limits* - FLD's[3], FLCs, parameters for blank holding forces and relationships between tool radii and defects of the drawn cup, are established.

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2. Kobayashi, S., "A Review Of The Finite Element Method And Metal Forming Process Modeling", *J. of Applied Metalworking*, Vol. 2, No. 3, July 1982.

   Levy, S., Shih, C.F., Wilkinson, J.P.D., and Stine, P., "Analysis of Sheet Metal Forming to Axisymmetric Shapes", in *Formability Topics - Metallic Materials, symposium*, May, 1977, Toronto, Canada, ed. B.A. Niemeier, A.K. Schmeider and J.R. Newby, American Society for Testing and Materials, 1977.

3. Keeler, S.P., "Understanding Sheet Metal Formability", *Machinery*, February-July, 6 articles, 1968.

   Goodween, G.H., "Application of Strain Analysis to Sheet Metal Forming Problems in the Press Shop", *SAE Paper 680093*, 1968.

   [Hobbs12], [Hosfo], recent IDDRG conferences.

Process modeling, an activity initially applied to *bulk* forming processes mainly, has recently been applied to sheet-metal forming, and may be extended to deep-drawing too ([Thoma], [BoerJ]). The process modeling of pressworking is concerned with deriving formability limits analytically and providing a theoretical insight into metal paths within the deformed zone. But such considerations are not yet to be *directly* used in the generation of new process designs[4]. Practical design manuals and guides ([Lyman4], [Wick], [HobbsL4], [Eary], [Jones], [WilsoHG]) recommend *engineering practice* rather than describe strict design procedures. While knowledge gaps and formal insufficiency do exist, they do not inhibit die-forming processes from being extensively used in the industrial world ([Eary], [Nagpa79]).

Deep-drawing covers a wide spectrum of flow conditions. In all these conditions the major principal stress is tensile and at least one surface of the deformed region is not supported by tools. The simplest process is a radial drawing in which a circular blank is drawn to a *straight, vertical, cylindrical* cup - abbreviated, henceforth, to *cupping.* In cupping, one principal strain is positive (tensile), the other is negative (compressive) and changes of thickness are small. Another combination of stresses - *biaxial-stretching* - where two of the principal stresses are tensile, results in significant thinning. In industrial usage, *sheet-metal forming* refers to processes performed on sheets, e.g. *stamping, die-forming* or *press-forming* requiring press operations involving dies, whilst *deep-drawing* pertains to the family of drawing and redrawing operations to produce cups.

Prediction of deep-drawability and start-of-flow conditions has been attempted using the main methods of plasticity and various experimental approaches. Several models have been proposed to predict deep-drawability. Jevons ([Jevon]), in 1940, elaborated on the metallurgical aspects of the

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4. Gegel, H.L., "Material Behavior Modeling - An Overview", in *Experimental Verification of Process Models - Proceedings of Symposium*, Cincinnati, Ohio, Sept. 1981, ed. C.C. Chen, American Society of Metals , 1983.

   Chen, C.C., *Experimental Verification of Process Models - Proceedings of Symposium*, Cincinnati, Ohio, Sept. 1981, American Society of Metals, 1983.

development of defects. He characterized relationships between crystal structure, their change during a draw, heat-treatments and related defects. Following Chung and Swift's research, some investigators devised simplified formulations to describe the principal phenomena in deep-drawing or stretching. Whiteley, in ([White], 1960) and Hosford, in his interpretation of Whiteley's paper ([Hosfo]), used the notion of homogeneous work to predict an *upper bound* limit draw ratio (LD), which mainly depended upon normal anisotropy. Hill ([Hill]) gives a slab-type analysis to predict a *lower bound* LD. A classical upper bound analysis based upon the changes of velocity within the die-bending zone, has been developed by Avitzur ([Avitz77]). It culminates in lengthy and difficult-to-apply expressions for the ram force. Woo ([Woo]) formulated the strains in the stretch forming region and Wang ([Wang82]) computed the force required to draw a sheet metal past a bead of constant cross section. Shortcomings in the analytical models led to the popular present usage of empirical tools, e.g. FLD's ("Keeler-Goodwin diagrams"[5]). But even using FLD's provides only small hints about the forming limits of complex draws.

Complex modes of drawing, e.g. of severely tapered draws and unconstrained redraws and operations that combine drawing and stretching, have been studied on a markedly limited scale. Furthermore, the application of the forming limit patterns of one-feature cupping to complex drawings is not a trivial matter. Redrawing has mainly been considered analogous to tube-sinking. Dedicated redrawing research has been conducted by Swift, in the early 40's, and later by Swift and Chung ([ChungSR]) to produce another comprehensive experimental study. This study was later developed by Willis ([Willi]). Fogg ([Fogg]) later studied the bending and straightening of the unconstrained region in redrawing through a conical die. By and large, generalized redrawing remains an empirical and experience-based domain.

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5. Keeler, Goodween *ibid*, [Nagpa79], [HobbsL9].

The following review summarizes a realistic analytical account of metal-flow. It is composed of empirically justified formulations only. The drawing of flat-bottomed cups - *flat cupping* - serves as a model for other patterns of flow which are not elaborated upon to the same level of detail. The analysis concentrates on determining minimal conditions to have the deformation completed, the *drawing limits* and the associated process variables. In composing the model, analytical knowledge has been given priority over empirical. The analytical part is based upon the works of [ChungSA], [JohnsMe], [Hosfo], [Slate], [Woo], [Fogg], and relies on drawing-limits formulations from contemporary literature. The empirical knowledge follows from that of [ChungSE], [HobbsL3], [HobbsL4], [Hobbs12], [Eary], [Wick] and [Lyman4].

3.2 Deep-Drawing of Axisymmetrical Cups

3.2.1 Metal Flow in Flat Cupping: Analytical-Experimental Characteristics

In general cup drawing, three types of forming regimes are found: *drawing, bending, stretching.* They are schematically illustrated in Fig. 4. Deep drawing processes include two modes of deformation: *drawing* and *stretching*, each of which contains bending. The *drawing* mode is the one that distinguishes cup drawing, and will be elaborated on first.

Drawing Mode

In *drawing*, the workpiece is caused to flow into the *die* cavity by a *punch*, and the flange edge may be constrained by a *blankholder*. A certain clearance should exist between the die-throat, the punch stem and the initial wall thickness of the blank. The general cupping process produces a flanged cup (Fig. 1). *Full cupping* refers to a drawing operation in which no flange is left. For the purposes of analysis, it is assumed its bottommost portion of the drawn cup assumes the exact shape of the punch and that the outer portion takes up that defined by the die. Hence, the inner wall of the cup assumes the size of the punch diameter and punch recess radius, while the flange bend assumes that of the die recess radius.

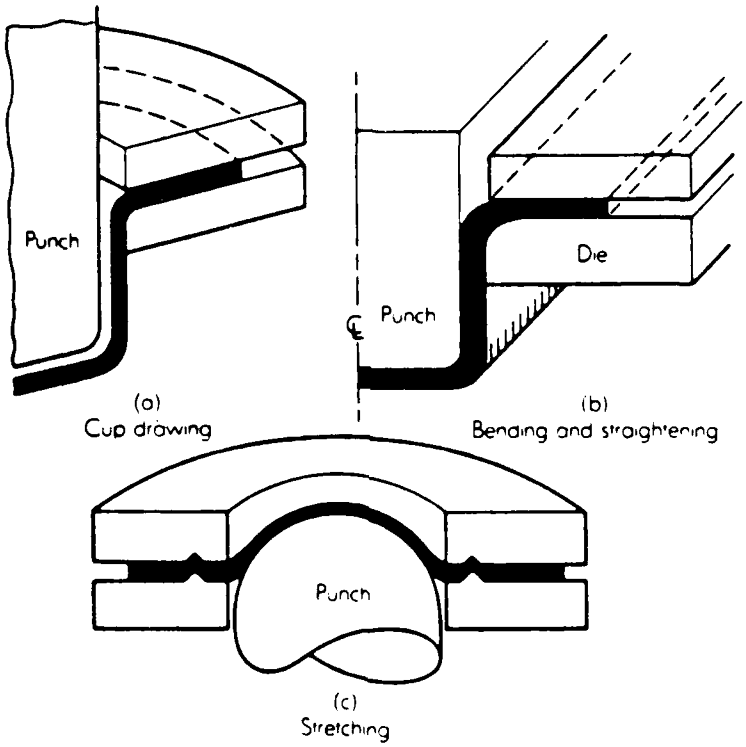


Figure 3-4. Primary forming modes ([Wick], Fig. 1-5)

Dimensions are taken from the "neutral line" or *medial* - i.e. the line of mean-change in length within the cross-section of a cup. Referring to Fig. 1, the following relations are thus established:

- $d_{cup} \equiv d_{cup\ mid\ wall}$.
- $d_{punch} + \frac{1}{2}\, t \simeq d_{cup} \simeq d_{die\ throat} - \frac{1}{2}\, t$,
- $r_{die\ fillet} \simeq r_{flange\ recess} - \frac{1}{2}\, t$,
- $r_{punch\ fillet} \simeq r_{wall\ recess} - \frac{1}{2}\, t$,
- conicity of the cup wall in vertical cupping is negligible ($\alpha = 0$).

A macro appearance, as in Fig. 5, shows the blank being converted progressively into the final cup with a flat ring of the blank becoming a cylindrical element.

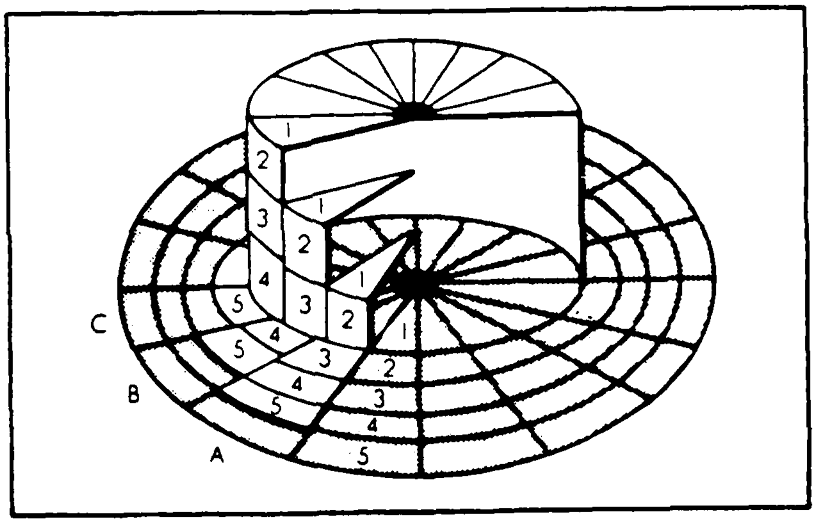


Figure 3-5. Progressive states in drawing a blank (from: [Wick], Fig. 4-41)

A closer look at the evolution of the drawn cup reveals:

- two major *phases*: *embossing* and *drawing*, both of which are nonsteady processes,
- five distinct zones of strain distribution, w.r.t. wall thickness deformation type, and
- six distinct regimes of deformation.

In the first phase, *embossing*, the shape of the fillet-radii of the tools is imposed on the blank. In the next phase, *drawing*, the flange is drawn and compressed towards the orifice of the die, bent around the die radius and pulled downwards to form a wall.

Phase I: Embossing

This stage produces the initial bending of the blank, as displayed in Fig. 6. At the beginning of the operation, the punch moves down and its face contacts the blank over its center - element #1. This element matches the punch face and does not undergo initially any deformation. As the punch moves on it carries element #1 down, causing the region contacting the punch radius to bend around it and assume the shape of the punch radius. This movement produces deformation *type E-1* and element #2.

As the punch moves down, the ring contacting the die radius is bent over it *in tension*, and assumes its contour. This deformation, *type E-2*, produces element #4. The boundary between elements #2 and #4, the zone that becomes the wall element, element #3, is yet of zero length. The embossing phase causes a slight drawing of the outer flange - element #5 - towards the center, with slight thinning of elements #2 and #4, due to the tension acting on them. Elements #1 and #5 remain stationary. Thinning and drawing at this stage are assumed, with solid empirical basis, to be relatively small, and are ignored here. The main deformation of this phase is *bending*. Bending and straightening forces are small compared with those required to compress or stretch the same ring (Fig. 17); the real draw has not yet started.

Phase II: Drawing

Once the initial embossing is over, *drawing* starts. As the punch moves down, the following deformations take place simultaneously:

The blank edge is drawn and compressed as it moves towards the die orifice. It is then bent and compressed over the die radius and straightened and pulled down to form a vertical cylinder, shown as element #3 in Fig. 7.

The regions of the cup being wrapped around the punch face and fillet, elements #1 and #2 of the embossing stage, are subject to tensile stresses under resisting frictional forces. If the flow stress is exceeded, these elements

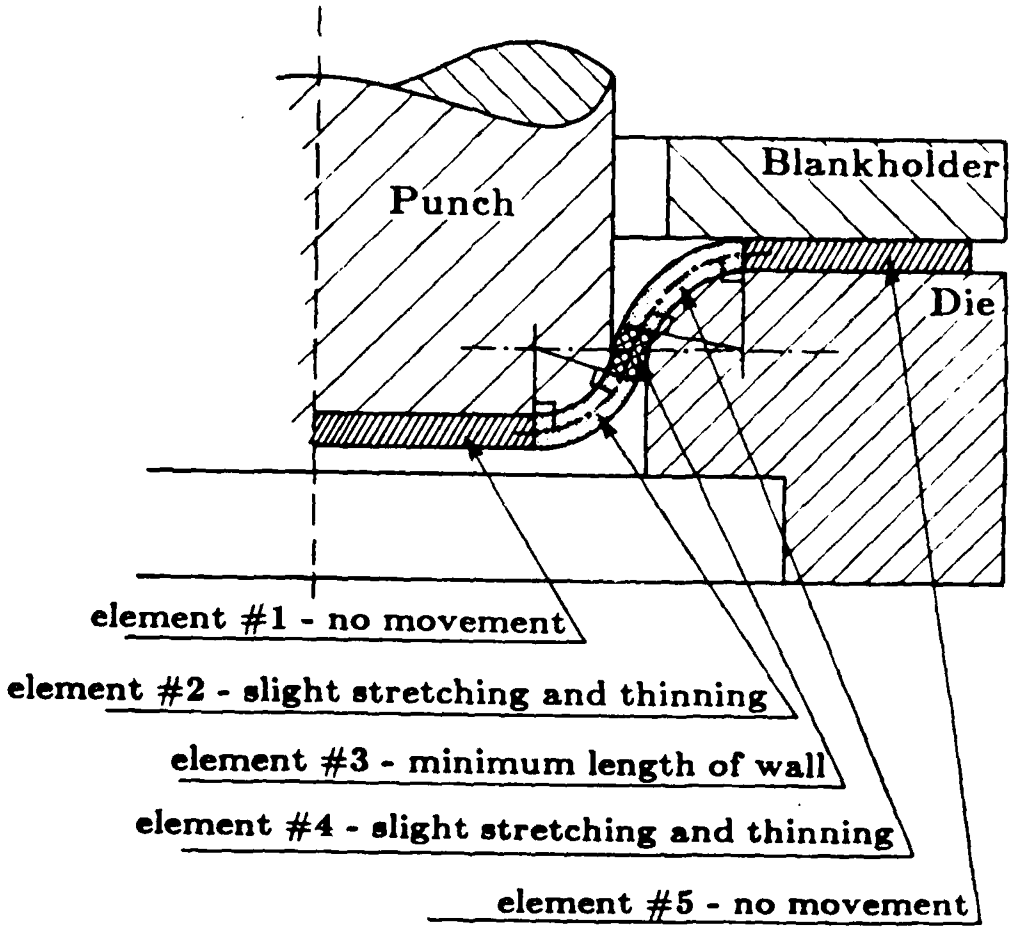


Figure 3-6. The embossing stage

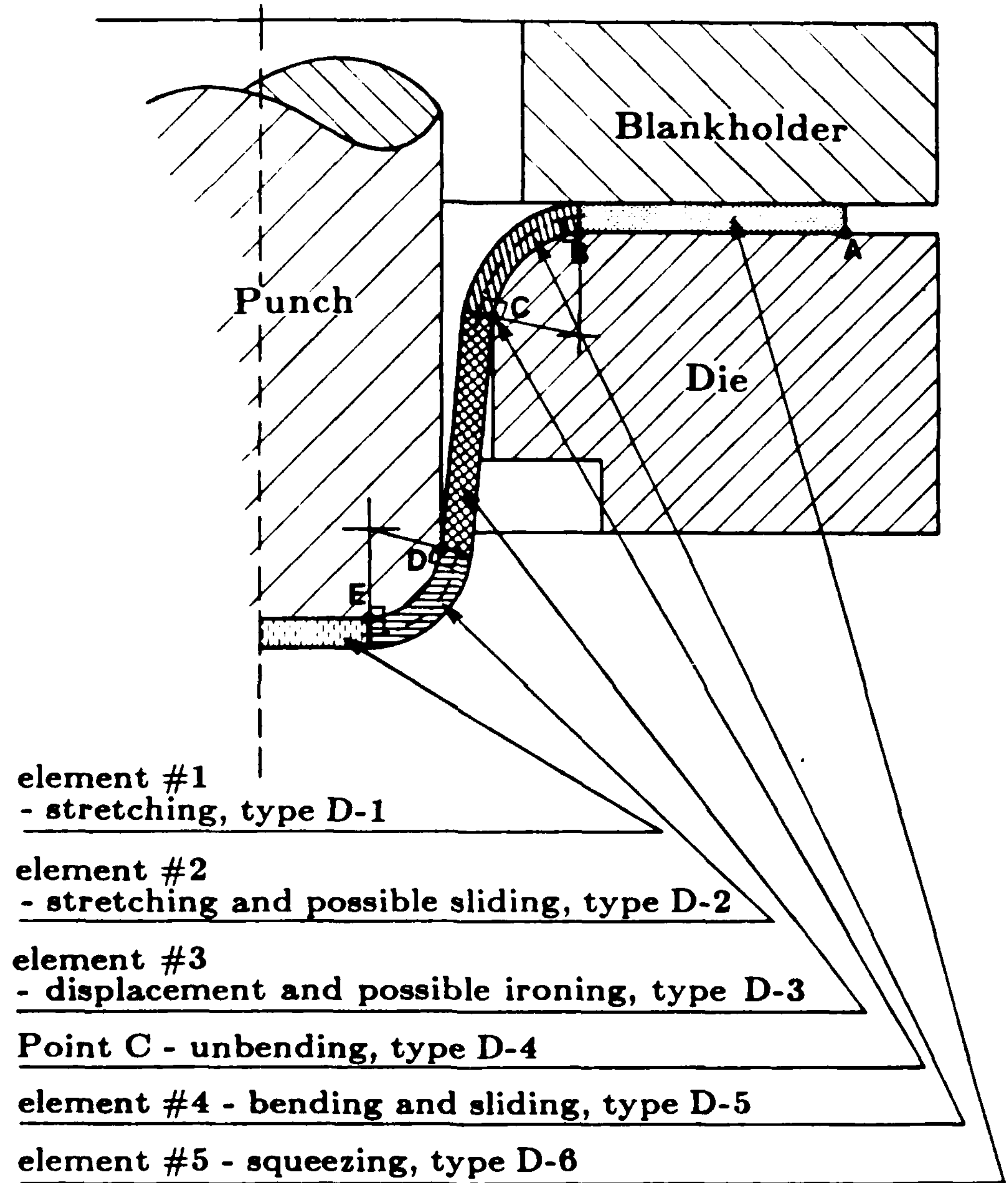


Figure 3-7. Flow regimes in flat cupping

are stretched and the region around the punch fillet slides over it to thin element #3. The possible stretching of the element #1 is denoted as deformation *type D-1*, and the sliding and possible stretching of element #2 as deformation *type D-2*.

The tension exerted on element #4 *straightens* it and pulls it down. The pulling-down operation - deformation *type D-3* - takes place in the clearance between the die throat and the punch stem. If the thickening of the blank does not exceed the available clearance, the wall can be displaced without having to be thinned, i.e. no *ironing* is required. If the effective stress in this region, which is the algebraic sum of the stresses induced by the punch pull (σ_1), the flange radial component of compression (σ_r) and the frictional stress (σ_μ) due to blankholding force, does not exceed the instantaneous flow stress, ***displacement*** rather than *stretching* takes place. The straightening of element #4, deformation *type D-4*, produces the upper part of element #3. Since this slab of metal has already been work-hardened by bending, straightening requires a greater force. Experiments pertaining to this part of the process, in which the punch force was measured, validate this analysis (see §.2.2).

In straightening, a material particle on the die-bend (element #4) is pulled, bent and made to slide over the die fillet radius, producing deformation *type D-5*. This movement is different from deformation *type E-2* in the embossing phase, in that *sliding* is now operative.

In pulling the blank edge inwards, towards the die orifice, deformation *type D-6*, ***blank squeezing***, occurs. A slab analysis (Table 1) for the stresses in the blank edge (element #5) shows that it is subject to the following stresses: radial drawing, a pair of friction forces and a pair of compressive forces that squeeze a trapezoidal slab into a more slender one, as its perimeter is shrunk. While being squeezed the slab tends to thicken increasingly towards the rim, where the deformation becomes pure circumferential compression. This process is schematically shown in Fig. 8.

It is evident that the compressed zones (elements #1 and #5) tend to thicken while the elements in the tensile regime (elements #3, #2 and #4) tend to thin. In [ChungSE] it is shown that, after minimizing blankholding and frictional effects, full cupping of 50% and 33% reductions respectively,

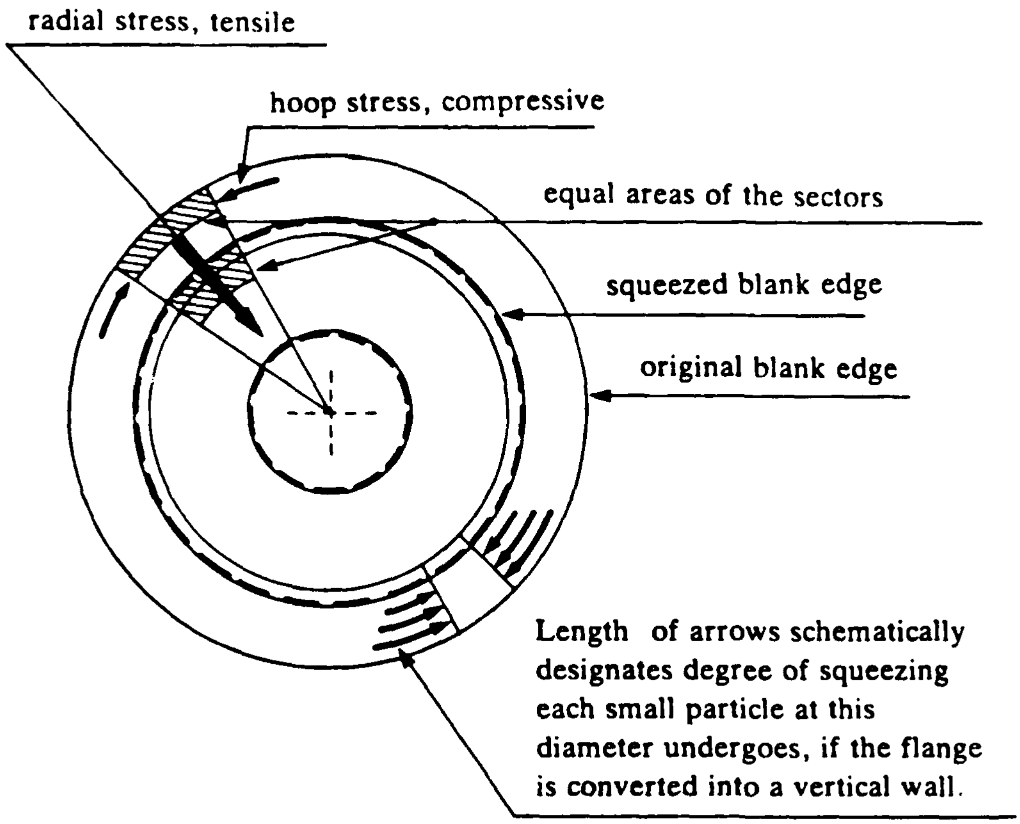


Figure 3-8. Schematic squeezing in pure radial drawing of a ring

resulted in 40% and 22% thickening at the blank rim. Stretching is the result of the instantaneous flow stress being exceeded in this *biaxial* tensile stress regime. Typical experimental observations of wall thickness strains are shown in Fig. 9.

The resultant strains produce five distinct regions, each liable to develop particular kinds of defects. These regions are schematically described in Fig. 10.

The regions most prone to thinning are the non-work-hardened ones, the border-zone between elements #2 and #3 near the punch radius, and, to a smaller extent, the border-zone between #1 and #2. The latter is less susceptible to thinning because of the added frictional resistance around the punch radius.

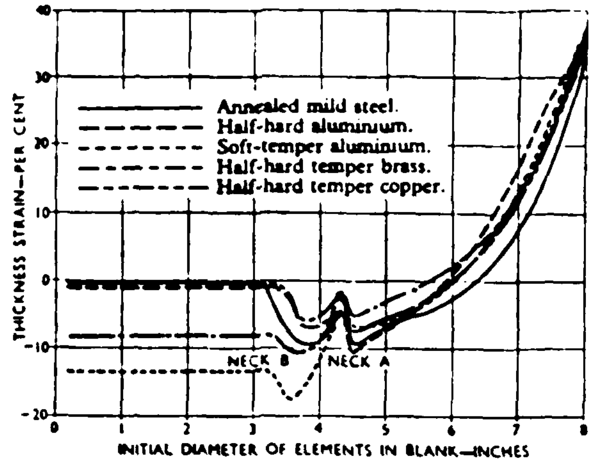
Varying strains, as induced in the compressed cup, result in varying degrees of work-hardening. A typical distribution of representative stress across the flange and the resultant flow-stress there are schematically shown in Fig. 11.

Deformation types and resultant flow characteristics within each regime are summarized in Table 1.

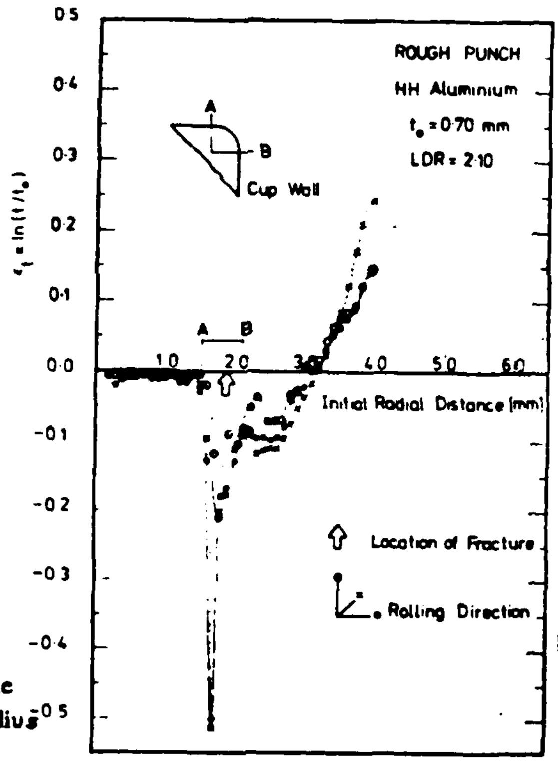
Stretching

In the idealized drawing described above, frictional forces did not constrain the flow of the blank edge into the die cavity but did prevent the bottom of the cup from being stretched to slide over the punch head. If the *blank* is constrained against flowing by either excessive friction or drawbeads that lock it, as shown in Fig. 12, *stretching* takes place. In pure stretching, as displayed by the hemispherical stretching mechanism of Fig. 12, a *one-phase* unsteady process dominates.

Unlike drawing, stretching inevitably results in *thinning*. A sheet stretched over a *rough* hemispherical dome reveals five regimes of deformation (Table 2). Initially the blank is planar. The hemispherical punch moves down to contact its center and performs the following deformations: It *embosses* a small element of the sheet, deforming it to a *spherical sector* (named henceforth element #1). Meanwhile, the ring external to that sector, becomes a *truncated cone* - element #2. Once this cone has been generated, the continued



a. (from [ChungSE] Fig. 23).



susceptible
punch radius

b. (from [Elseb], Fig. 6d).

Figure 3-9. Wall thickness strains in cupping (after [ChungSE] and [Elseb])

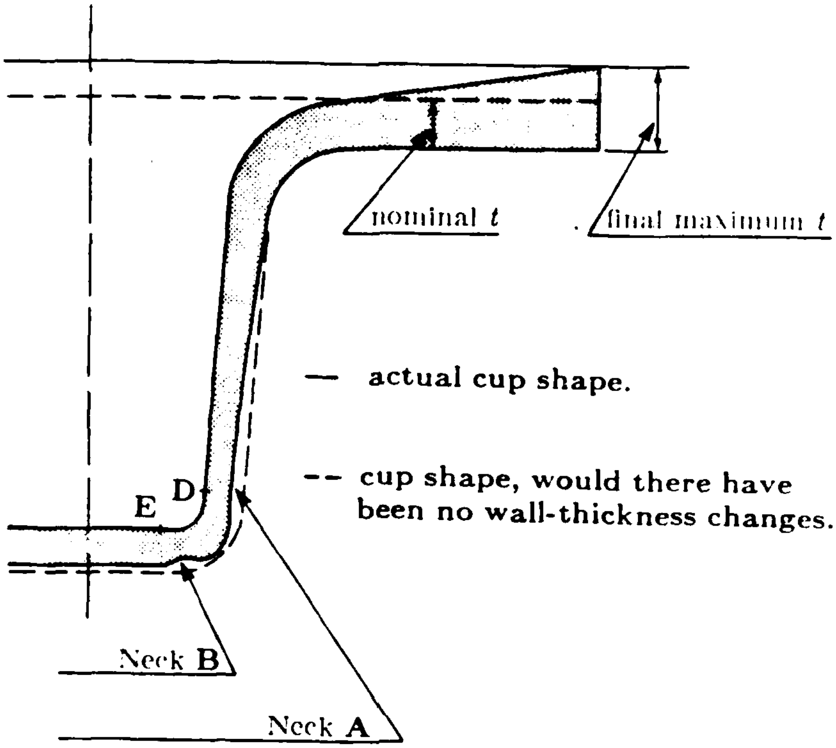
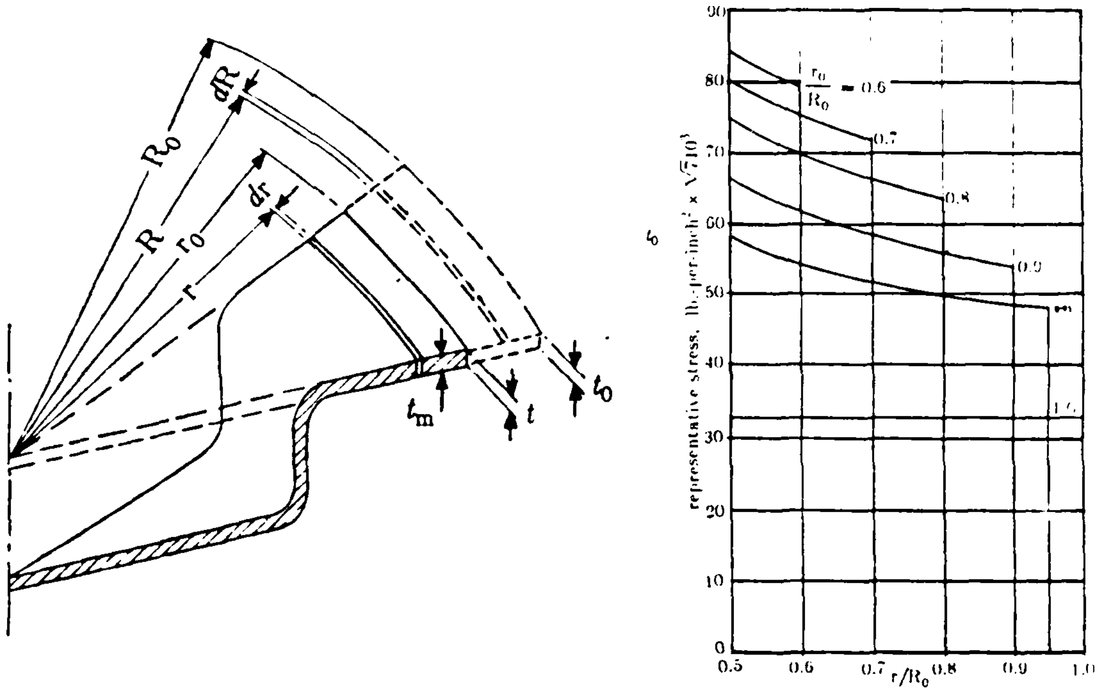


Figure 3-10. Schematic profile of wall-thickness changes in a flanged cup (after [JohnsMe], Fig. 11.11)

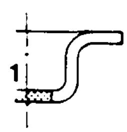
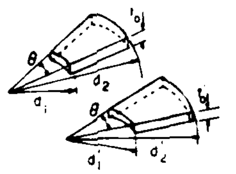
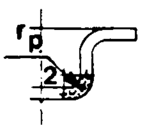
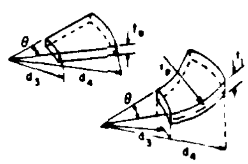
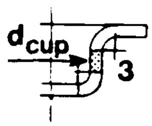
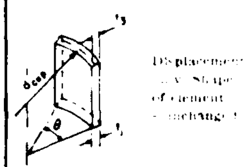
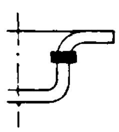
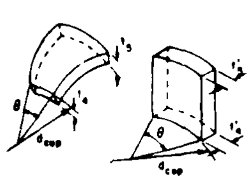
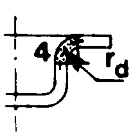
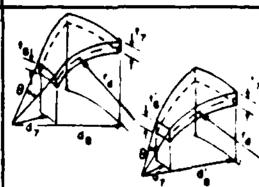
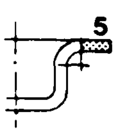
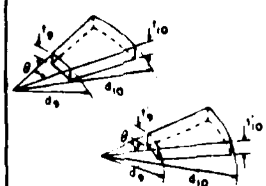


$\bar{\sigma} = 12{,}250 + 30{,}700\ \epsilon^{0.49}$,

$\dot{\epsilon} = 3 \cdot 10^{-4}/\mathrm{sec.}$, with yield criterion: $\sigma_r - \sigma_h = \sqrt{7}\ \bar{\sigma}$.

Figure 3-11. Representative stress distribution and resultant work-hardening in cupping (after [ChungSA], Figures 30a and 33b)

TABLE 3-1. Deformation Regimes in Flat Cupping

Deformation Regimes in Flat Cupping*				
Type of Deform	Element # & Location	Particle in Element: Initial, Final	Forming Regime	Principal Affecting Variables
1 - bottom stretch			Bi-axial tension against friction with possible stretching	• $Y_{initial}$ • $\bar{\sigma}-\bar{\epsilon}$, • friction at punch face, • resistance to thinning - R.
2 - punch-fillet stretch			Biaxial stretch combined with bending and sliding	• $Y_{initial}$ • $\bar{\sigma}-\bar{\epsilon}$, • friction at punch fillet, • resistance to thinning - R.
3 - wall-displacement			Axial tension against friction with possible stretching	• $Y_{instantaneous}$ • $\bar{\sigma}-\bar{\epsilon}$, • punch-wall friction, • die-punch clearance, considering t; avoid ironing. • friction along punch wall resists sliding
4 - straighten			Unbending under tension	• $Y_{instantaneous}$ • degree of straightening.
5 - die bend & slide			Bending and sliding under tension	• $Y_{instantaneous}$ • DRR, DRT, • ability of flange fillet to buckle
6 - blank squeeze			Circumferential squeezing under radial tension	• $Y_{instantaneous}$ • ability of flange edge to buckle • compressibility of blank edge, • directionality of ductility (ΔR)

* For brevity, the drawing stress is omitted from each type of deformation.

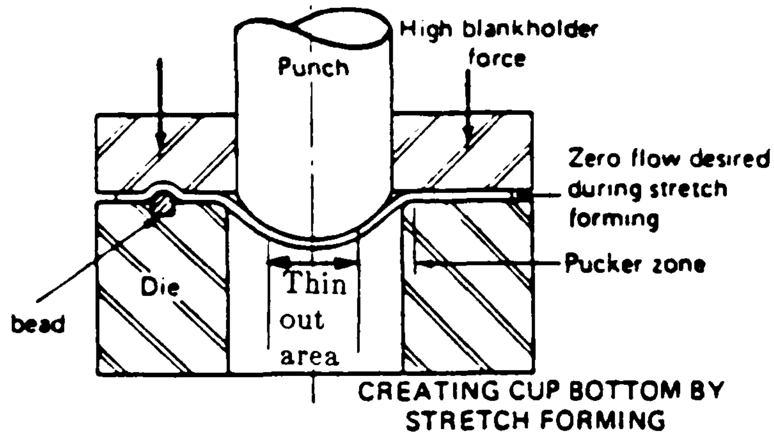


Figure 3-12. Hemispherical stretching (after [Eary], Fig. 157)

movement of the punch causes a small conical ring of that cone (element #2) to undergo bending and assume the contour of the punch. The contoured ring becomes a spherical sector in continuation of element #1, and produces element #1′. Hence this deformation, *type S-1*, is named ***contouring***. The rate of bending in contouring w.r.t. to heat dissipation is not severe. Contouring is accompanied by *pulling* down the *free* truncated cone between the contact line of the punch and the die orifice - deformation type *S-2*. This deformation stretches the cone, in both radial and circumferential directions, to produce a conical element of steeper edge (element #2′). Simultaneously, the throat of the flange continues to undergo simple bending, deformation ***type*** *S-4*, similar to deformation ***type*** *E-2* in the embossing phase of drawing. As the punch moves further down, the next encountered tapered element - element #2′ - is already stretched, and thus strain-hardened. In ideal stretching, the section that has already been contoured is restrained against being stretched on and slid along the punch dome by high frictional force. Hence, contouring will continue to form the next conical segment into a spherical sector. As an element of the free conical section approaches the punch contact line its hoop strain decreases, due to constraints induced by neighboring elements, while the radial strain is kept increasing.

As long as necking in biaxial tension is avoided, the process goes on until the end of the punch travel or the start of pure cylindrical stretching. In *cylindrical stretching* - deformation *type S-3* - uniaxial tensile stress stretches the cylinder while the punch stem prevents the shrinking of its diameter, thereby producing a cylinder of thinner wall - element #4. Since the flange is held tight against sliding, its portion between the fixed rim and the die orifice - element #5 - is allowed to flow under plane biaxial stretching - deformation *type S-5*.

Wall-thickness changes in a stretched cup are described schematically in Fig. 13.

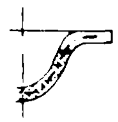
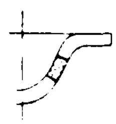
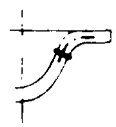
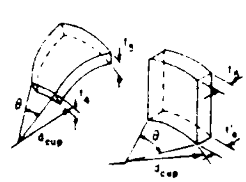
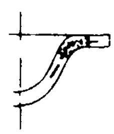
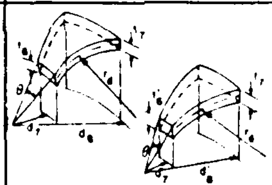
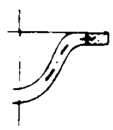
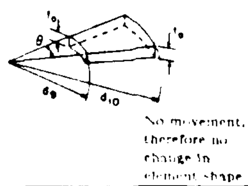
Combined Draw and Stretch Mode, Stretch Forming

As long as the drawing mode prevails, the effective stress induced by the punch exceeds the *instantaneous* flow stress throughout the free flange of the blank (out to the rim), and flow continues. Flow in the outermost ring of the flange may be delayed or completely halted as a result of high resisting frictional stresses (σ_μ), or high flow stress, due to work-hardening . Flange thickening towards the rim amplifies both causes. Thus, in the later stages of a draw a combination of stretching and drawing is more apparent, with varying contributions from each mode. The moment the blank edge is held fixed, or the flow in it is restrained, stretching becomes the dominant mode of deformation. If, in the above shown *stretch* mode (Fig. 13), the material in the flange could flow while contouring takes place, *stretch forming* mode occurs. In this case *contouring* would stretch a conical ring, but *tapering* - deformation *type S-2* - would become a deformation of the *drawing* mode type. The stretch-forming mode is attained when friction between the domed punch and cup bottom prevents sliding while the flange can still flow.

Examination of a combined drawing-stretching flow regime reveals the border between the *drawn* and the *stretched* zones - the *die impact line* - as in Fig. 14.

In pure stretching (blank held fixed and no sliding over the punch head) *n* (strain hardening exponent) becomes an important factor that largely determines *stretchability*. Hence, in combined drawing-stretching operations, a

TABLE 3-2. Deformation Regimes in Pure Stretching

Deformation Regimes in Pure Stretching*				
Type of Deform	Element # & Location	Particle in Element: Initial, Final	Forming Regime	Principal Affecting Variables
S-1 contour			Stretch and bend tapered element	• r_{dome} • $Y_{instantaneous}$
S-2 taper & stretch			Biaxial stretching	• $Y_{instantaneous}$ • $\bar{\sigma}-\bar{\epsilon}$ • ability to buckle
S-3 cylinder stretch			Axial tension	• $Y_{instantaneous}$, • $\bar{\sigma}-\bar{\epsilon}$, • length of stretch, • directionality of ductility (ΔR).
S-4 die bend			Bending under tension, and sliding if stretching occurs	• $Y_{instantaneous}$ • $\bar{\sigma}-\bar{\epsilon}$ • r_{die}
S-5 plane stretch			Plane biaxial stretching	• $Y_{instantaneous}$ • $\bar{\sigma}-\bar{\epsilon}$

* For brevity, the drawing stress is omitted from each type of deformation.

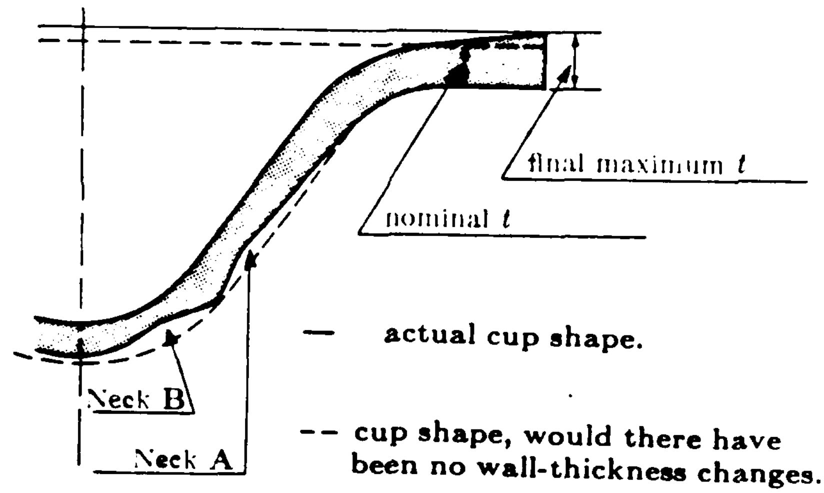
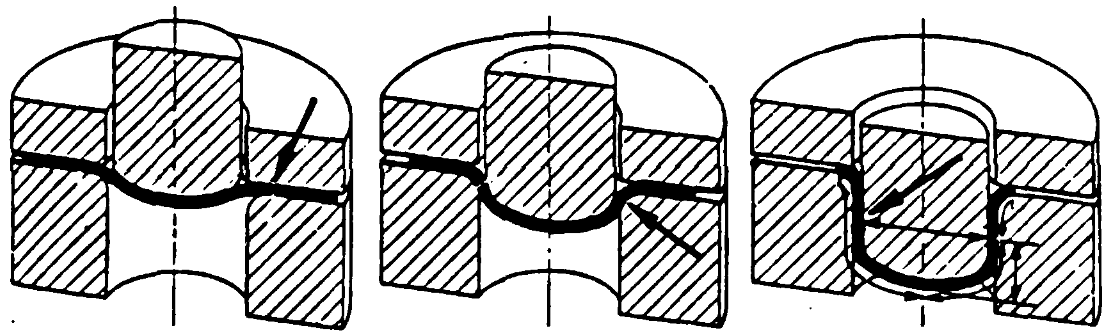


Figure 3-13. Schematic profile of wall-thickness change in a stretched cup



"→" points to the die impact line

Figure 3-14. Die impact line ([HobbsL4], 4-16)

specification for a composition of drawability-stretchability properties can be prescribed if the local limiting strains can be stated. Industrial operations often combine different modes and successive operations into a single composite one. Thus, in industrial practice it is often found, that not only are drawing and stretching modes combined into one operation, but *ironing* is also incorporated (Fig. 15) and special paths of deformation, like tractrix[6] drawing, as in Fig. 16, help to overcome limiting draw ratio (LD) constraints.

3.2.2 Start-of-Flow Conditions

The drawing mode can start and proceed if the effective stress at each deformed zone surpasses the instantaneous flow stress, and if friction or hold-down mechanisms do not prevent the flow. If the latter condition is not satisfied a stretching mode will take place. For *stretching* to proceed the effective stress must surpass the flow stress in biaxial tension. In both cases, the effective stress is created by the punch load and hence a start-of-flow study is concerned with the punch load required to initiate flow.

Punch Force in Drawing

Experiments show that a punch-load - travel diagram has the kind of characteristic seen in Fig. 17.

A punch load - travel diagram shows that the load required to *emboss*, straighten and overcome static friction so that compression and sliding can start, accounts for $\simeq 60\%$ of the full thrust. After compression starts, the load increases (due to work hardening) to a peak, typically within a region extending over $\{1/3$ to $2/3$ of the stroke$\}$ depending upon the $\bar{\sigma}-\bar{\epsilon}$ characteristic. Momentary zero load is recorded on the boundary between the end of compression and the final straightening. Once the full cup is attained,

6. Tractrix is the locus of the points lying on the outside lip of a cup being drawn without a blankholder, see Fig. 16.

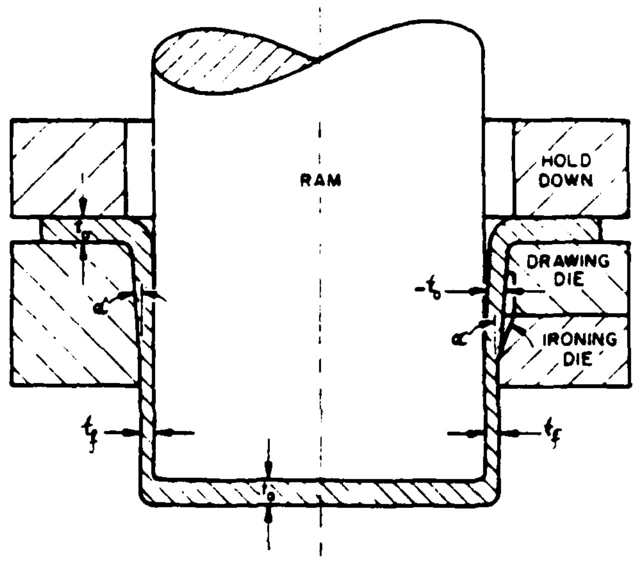


Figure 3-15. Ironing taking place within a deep-drawing operation ([Avitz], Fig. 10.25)

plastic deformation ends and a simple displacement downwards takes place, provided that no ironing is required. The displacement may still require some punch-load, as in the case where wall springback produces a resisting frictional force. The zero-load point is not encountered in real-life drawing, although the straightening peak can be identified because of the presence of frictional, and sometimes ironing, forces at the cup wall. A typical real-life diagram is shown in Fig. 18.

Although the basic factors that contribute to punch load in deep drawing have been known for more than 50 years[7], analytical work has not been able to contribute much to practice, partly because of information gaps resulting from the testing of materials under biaxial stresses. Contemporary analytical models can only partially cope with the complexity of punch load characteristics. This has led the pressworking industry to the use of a collection of empirical equations, mostly needed for the greatest required force.

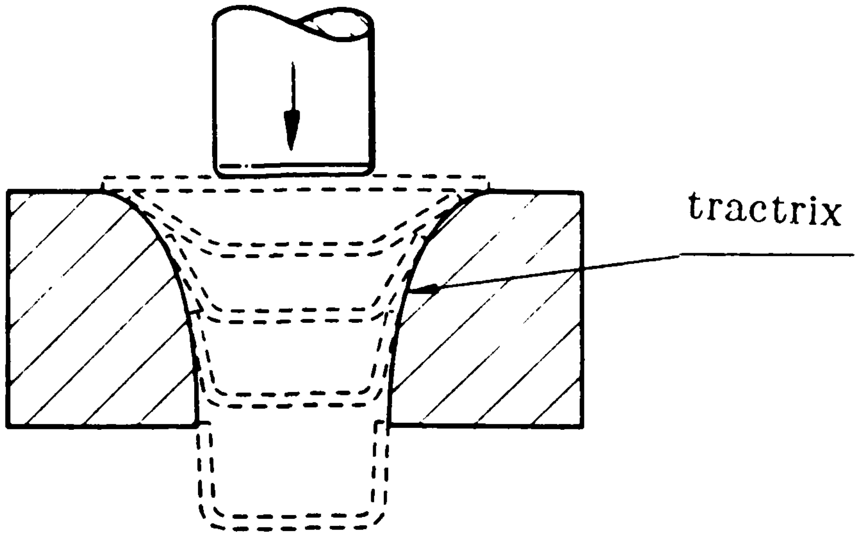


Figure 3-16. Successive stages in tractrix drawing (after [Avitz], Fig. 10.15)

Such expressions are found in abundance in industrial handbooks and practical pressworking guides. Some of the most common ones are quoted below.

Eq. 1.[8] $P_{max} = 2\,\pi\, r_{cup}\, \sigma_U\, (D - C)$

C is a constant, $\{0.6 < C < 0.7\}$.

Eq. 2.[9] $\lceil P \rceil = K_1 \cdot \sigma_U \cdot L \cdot t$

$\lceil P \rceil$ designates an upper bound estimate for the punch force,

L the cup circumference at the smallest cross-sectional area, and

t the cup wall-thickness at the smallest cross-sectional area,

$K_1 = 1.2\,(D - 1)\,/\,(LD - 1)$

7. Sachs, in 1934, *ibid.*
8. A.S.T.E. ***Tool Engineers Handbook***, 2-nd edition, McGraw-Hill, N.Y. 1959.
9. synthesized from: [Wick] and [WilsoHG].

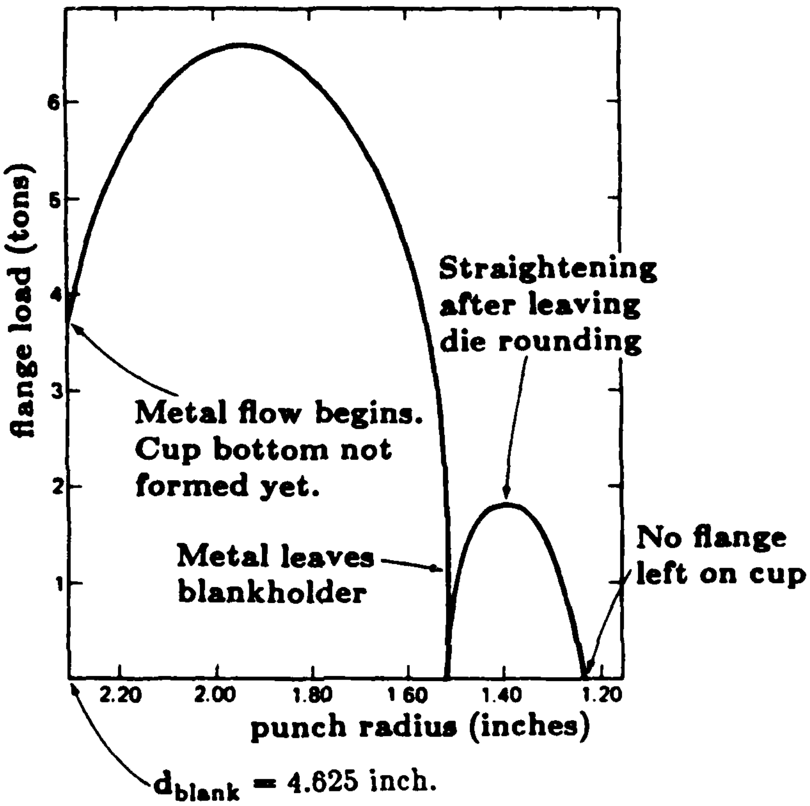


Figure 3-17. Drawing with a 2.5_{inch} diameter punch: schematic punch-load - punch-travel diagram (after [Eary], Fig. 127)

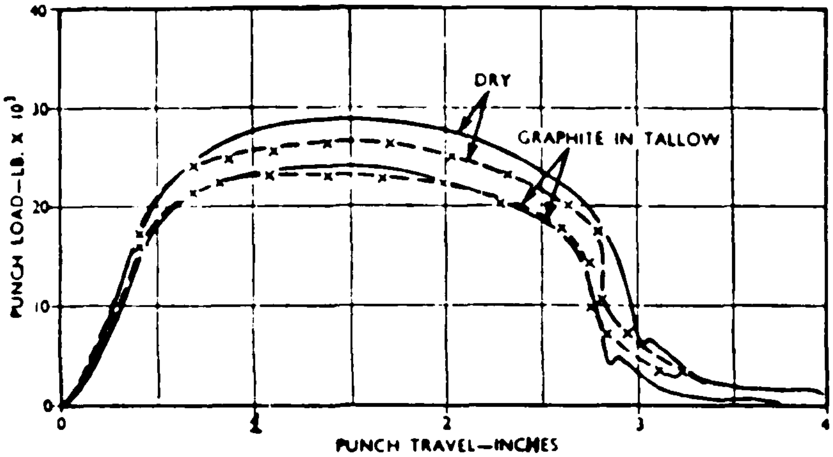


Figure 3-18. Punch-load - travel diagrams ([ChungSA], Fig. 42, in the part that studies lubrication effects)

Eq. 3.[10] $[P] = K_2 \cdot \sigma_U \cdot L \cdot t$

K_2 is a coefficient that depends upon D. Typical values for full cupping are given in Table 8 of the implemented rule, see Rule #89.

These expressions refer to *drawing* modes. A pronounced shortcoming of such expressions is their limited applicability. They are not valid when more composite draws and redrawings are evaluated, i.e. when the role of bending, unbending and friction is significant. It is therefore preferable to utilize an analytical expression, provided that it significantly correlates with experimental evidence. In the wake of the absence of a complete analytical expression for the punch load, *approximate* expressions which usually employ the above set of assumptions, are sought.

Backofen ([Backo], §11) has computed the maximum required drawing force using the above assumptions. Thus,

Eq. 4. $P_{max} = 4\,\pi\,\sigma_T\,r_{punch}\,t\,/\,\sqrt{3}$.

10 [HobbsL4] upon R.M. Hobbs. BHP Technical bulletin, Broken Hill Proprietary Co. Ltd.

Hosford ([Hosfo81]) assumed that the proportion of the combined contribution of the plastic work in bending and unbending, and in overcoming friction can be related to the drawing force that can be sustained by the walls;

Eq. 5. $P_{max} = \frac{1}{\eta}\, 2\,\pi\, r_{(w)}\, t\, \sigma_{(f)}\, ln\left(\frac{d_{blank}}{d_{cup}}\right).$

Slater ([Slate]) estimated the greatest punch force as

Eq. 6. $P_{max} = 2\,\pi\, r_{(w)}\, t_0\,.$

Duncan and Johnson ([DuncaJo]) present *instantaneous* estimates for punch-load that may be adapted for practical usage. The first approximation using slab analysis extracts the punch load as if flange squeezing only takes place. Then, for negligible wall thickness changes and a uniform yield stress, the precise punch force is,

Eq. 7. $P_{cur} = \pi\, d_{cup} t_0\, m\, A_1 \left(1 + \frac{A_2}{2A_1}\, ln(A_3)\right) ln\left(\frac{d_{flange_{cur}}}{d_{cup'}}\right).$

$d_{cup'}$ is the mid-wall diameter of cup,

m is the empirical constant for the modified Tresca yield criterion with $m = 1.1$,

A_1 and A_2 are constants in the $\bar{\sigma}$–$\bar{\epsilon}$ relationship, $\bar{\sigma} = A_1 + A_2\bar{\epsilon}$, and

$$A_3 = \left[2D^2 - \left(\frac{d_0}{d_{cur}}\right)^2 + 1\right] / \left[\left(\frac{d_0}{d_{cur}}\right)^2 + 1\right].$$

Combining the principles of *work analysis* and *mean work analysis* with the previous assumptions, expressions for the greatest required punch load are:

Eq. 8. $P_{max} = {}^1\!/_2\, \pi^2\, d_{cup} t_0\, A_1\, (A_4 - 1)\left[\frac{2D^2\, ln(D)}{D^2 - 1}\left(\frac{A_4\, ln(D)}{A_4 - 1} - 1\right) + 1\right] / \sqrt{3}.$

A_4 is $\frac{A_2}{\sqrt{3}\, A_1}$.

Eq. 9. $P_{max} = {}^1\!/_4\, \pi^2\, d_{cup} t_0\, (\bar{\sigma}_0 + \bar{\sigma})\, ln\left(\frac{D^2+1}{2}\right) / \sqrt{3}\,.$

Tests to verify the approximations given in equations #7, #8 and #9 were carried for *flat cupping* only and within a limited set of drawing conditions. They showed that the first and second approximations, i.e. equations #7 and #8, lack satisfactory correlation with experimental results. The third approximation - equation #9 - has a reasonably good predictive power, and will therefore be used to form a rule.

An upper bound analysis, developed by Avitzur ([Avitz77]) includes flow along a die bend and leads to complicated, not-directly-applicable relationship for the punch force. Assuming wall thickness constancy, the field of changing velocity directions is described in Fig. 19. After a series of simplifying assumptions, the punch force is described there ([Avitz77]) as a function of: DRR', TR'[11], D, η, and $F_{blankholding}$.

3.2.3 The Emerging Cup: Strains, Defects and Failures

Two common modes of *failure* are found in flat cupping: *tearing* of the cup wall and *buckling* at the flange or the die orifice. Tearing in the drawing mode occurs when the tensile flow stress at one of the local necks (Fig. 10) exceeds the ultimate stress (σ_U). That point is referred to in the literature as a *forming limit*[12]. In the context of process planning and use of the resultant cup, an arbitrary distinction between defects and failures is introduced. *Defects* in deep-drawing refer to a final undesirable geometry or surface finish of cup. Defects are distinguished from failures in that they are developed *locally* and do not prevent the completion of the draw. Frequent defects in die-forming are *wrinkling, puckering, exaggerated-earing, wall thinning, edge-cracking* and *orange-peel*, as shown in Fig. 20. They result from either buckling, excessive tensile stresses, asymmetric flow or improper lubrication.

11. DRR' and TR' are there defined slightly differently from the DRR and TR above, as $DRR' = r_{die\ rounding} / d_{outer\ toroid\ die\ bend}$ and $TR' = t / d_{outer\ toroid\ die\ bend}$.

12. For example see: [Wood], Keeler, Goodween, *ibid*, [Wick], *Mechanics of Sheet Metal Forming*, ed. D.P. Koistinen and N.M. Wang, Plenum Press, 1978.

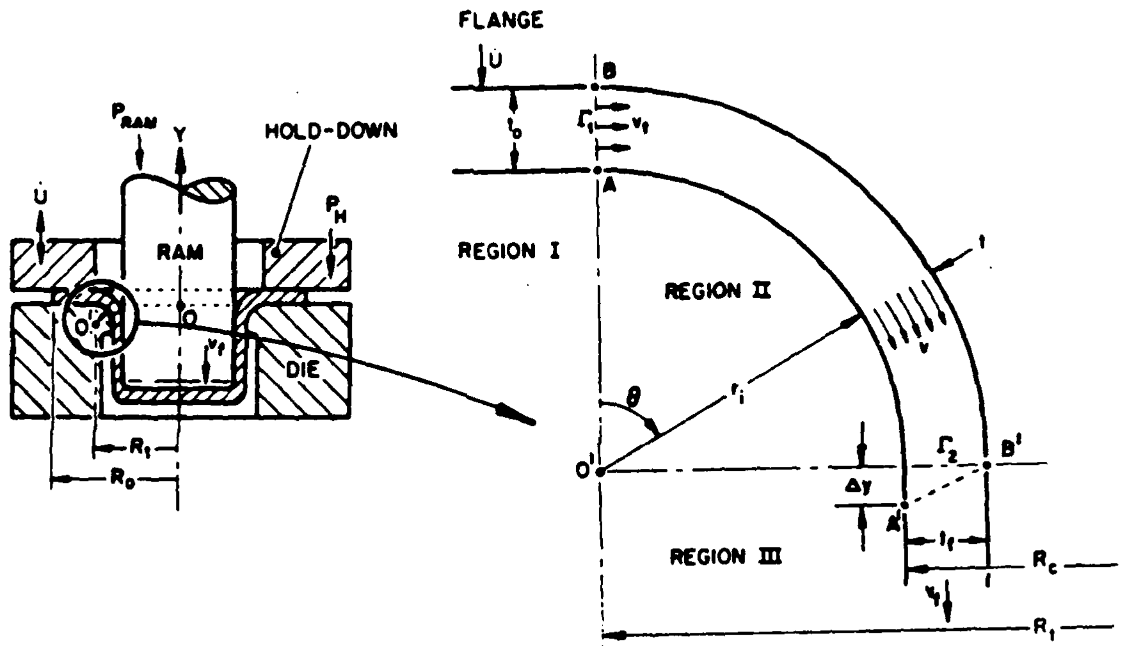


Figure 3-19. Cup drawing and velocity fields over a die bend (after [Avitz], Fig. 10-37)

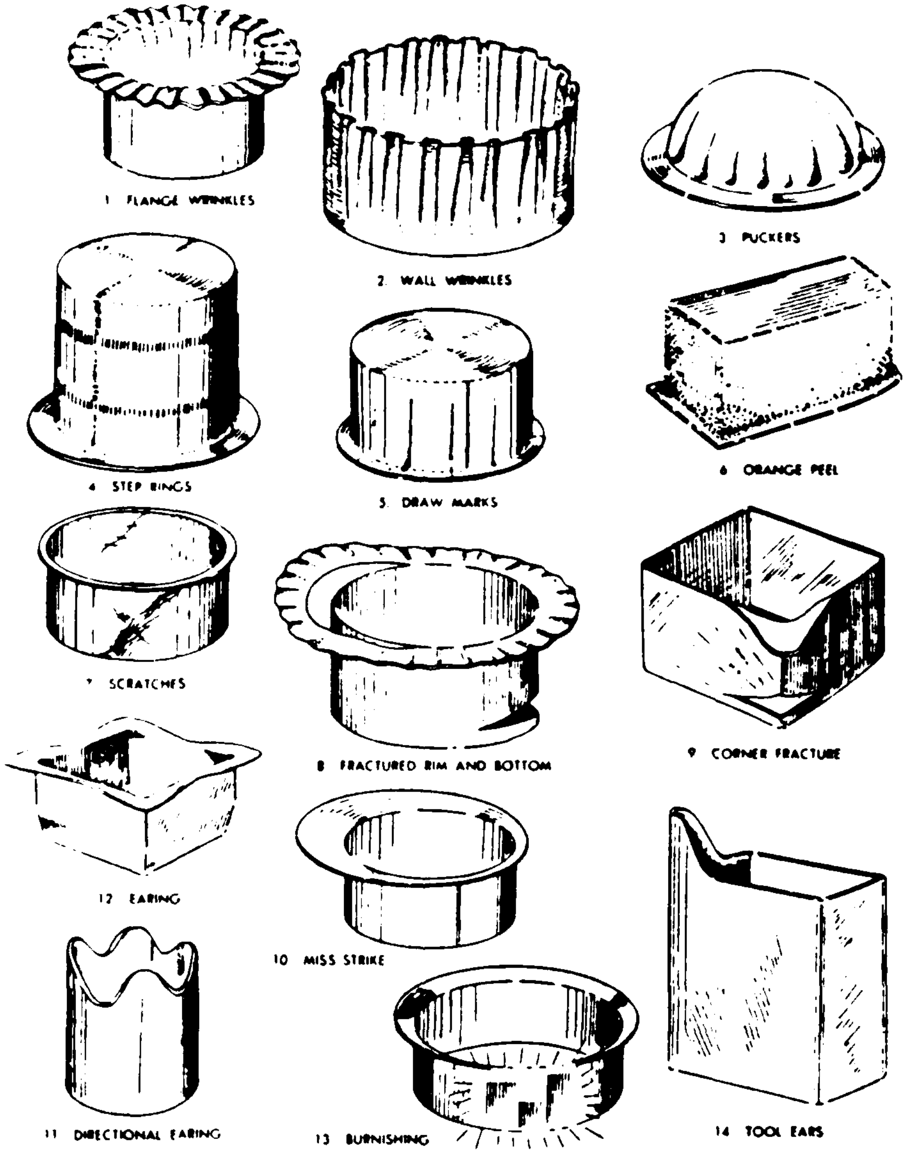


Figure 3-20. Typical deep-drawing defects ([Eary], Fig. 135)

Tensile failures and defects frequently occur in drawing and stretching. Once stretching exists, the cup undergoes thinning in the region where $\bar{\sigma} > Y_{\text{instantaneous}}$. An analytical and experimental characterization of wall thickness change in stretch-forming produced by hemispherical cup drawing, is given by Woo ([Woo]), as is shown in Fig. 21.

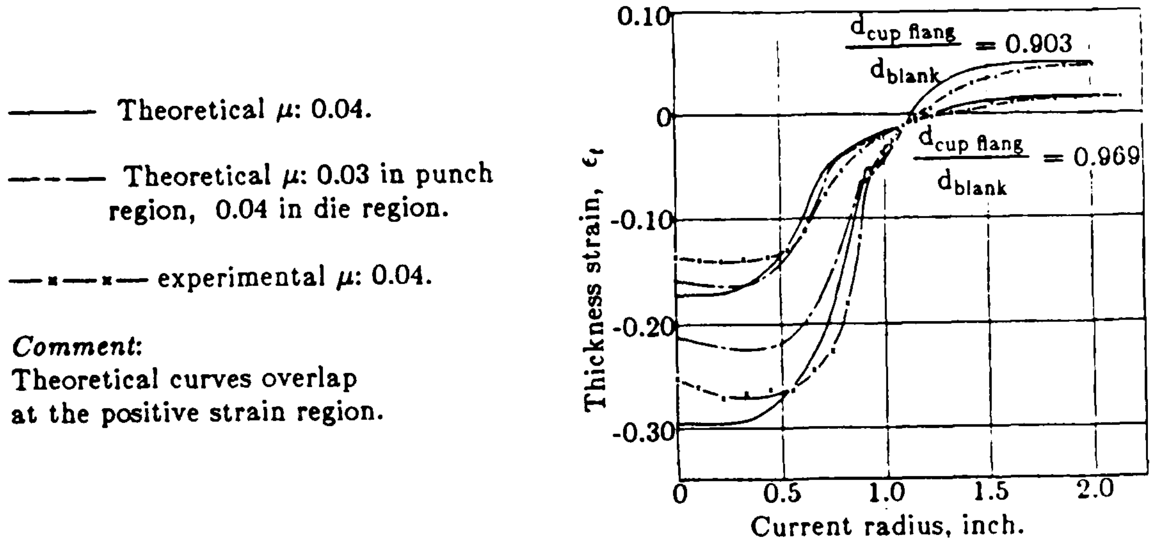


Figure 3-21. Analytical and experimental distribution of thickness strain in hemispherical cup drawing (after [Woo], Fig. 13)

The relationship between radial and hoop strains in a drawn cup can be measured by mapping a blank, as demonstrated schematically in Fig. 22.

Since various elements of an initial blank undergo different sequences of forming regimes (history), they are thus susceptible to different forms of failures and defects. Table 3 shows the relationship between strain path and liable failures and defects. The elements of the initial blank and their final configuration are defined in Fig. 1.

Tensile Failures

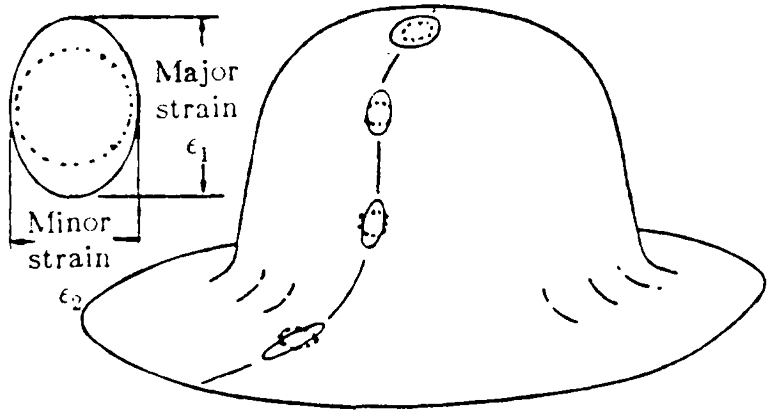


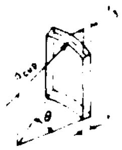
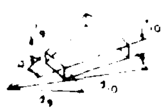
Figure 3-22. Schematic shapes of deformation in drawing ([Hobbs12], Fig. 12-1)

Failures in deep drawing under tension are usually caused by *plastic instability* rather than *fracture.* Nonetheless, the two most common measures of *tensile ductility*: - ***reduction in area*** and ***total elongation*** do not correlate significantly with drawability. In drawing under biaxial tension (as in stretching) a common failure develops in the form of a ***localized neck***. Analytical predictions of instability and flow localization in sheet-forming ([Semia]) give the onset of instability in terms of either $d\bar{\sigma}/d\bar{\epsilon}$ (Swift and Hill) or the dimensions of a flat specimen (Marciniak-Kuczynski). These formulations cannot yet be readily translated into terms of the change in cup shape and the external drawing stress (a research topic suggested by [Semia]).

3.2.3.1 Wall-Thickness Changes

Thickening of the blank edge is important for determining blankholding clearances and assessing the likelihood of wrinkling. [Lyman4] gives an empirical expression for flange thickening in the *drawing* mode as

TABLE 3-3. Susceptibility to defects and failures depending upon deformation path

Paths in flat cupping and possible failures and defects			
Route #	Resultant Element	Sequence of Deformation Types	Liable Failures and Defects
1	**#1** 	**D-1**	• Overthinning.
2	**#2** 	**D-2 → D-3**	• Excessive springback. • Cracks in bending • Tear at points D or E.
3	**#3** 	**D-6 → D-5 → D-4 → D-3**	
4	**#3** 	**D-6 → D-5 → D-4**	• Puckering near point C.
5	**#4** 	**D-6 → D-5**	• Cracks in bending.
6	**#5** 	**D-6**	• Wrinkling near edge-lip.

Eq. 10. $TT_{flange} = -\sqrt{D}$.

In the stretching mode, assessment of thinning is treated analytically and experimentally. Mellor[13], uses the following thickness strain measure in the ideal *stretch forming* mode for evaluating *bulge test* results:

Eq. 11. $\epsilon_t = -2\ ln\left(d_{dome} / d_0\right)$.

[Lyman4] gives the empirical measure for wall-thickness thinning (TT) as

Eq. 12. $TT = (d_{blank}^2 + h_{hemisphere}^2) / d_{blank}^2 = 1 + (h_{hemisphere} / d_{blank})^2$.

3.2.3.2 Dimensional Accuracy

Deep drawing can be carried out to high degrees of precision, e.g. to maintaining inside wall diameter to within 0.0005 of diameter. Maintaining the straightness and/or angularity of flanges is a much harder task. The accuracy of a drawn cup is affected by the tools, the metal condition, the drawing techniques, the press condition and the amount of springback. The latter is due to self equilibrating elastic residual stresses acting throughout the differentially plastically deformed zones, once the cup is removed from the punch. The amount of the springback — distortion depends upon the geometry of the deformed cup, the geometry of the die-bend zone, the $\bar{\sigma}$—$\bar{\epsilon}$ relationship and the wall-thickness ratio. Springback can be reduced by introducing in-process annealing and by reducing the drawing-ratio of each pass. Due to insufficient engineering data this subject will be further dwelled upon in the context of defects only.

13. Mellor, P.B. "The Ultimate Strength of Thin-Walled Shells and Circular Diaphragms Subjected to Hydrostatic Pressure", *Int. J. Mech. Sci.*, p. 216, Vol. 4, 1956.

3.2.3.3 Drawing Limits

Drawing limits refer to the occurrence of process failure by either necking in tension or buckling under compression. Theoretically possible failures at the ultimate compressive stress are not encountered in deep-drawing. Deformation *type D-6*, the squeezing of the flange, produces a strain gradient towards the outer rim. This can be visualized by conceiving the flange as a series of concentric rings, each being squeezed inwards. The farther out is the compressed ring (w.r.t. die orifice) the more (hoop) strained it becomes. Consequently, the flow-stress of strain-hardening materials increases towards the rim, see Fig. 11, regardless of whether or not a flange will remain. Hence, for strain-hardening materials, continuing to squeeze the blank edge requires higher drawing stresses but the LD is affected only if σ_{t} is reached.

The tensile stress is transmitted through the "weakest links" in the cup, i.e. points D and E. These are subject to almost no strain-hardening during the embossing phase and therefore changes in the starting flow stress or in n will have negligible effect on the drawing limits. This qualitative reasoning is verified experimentally, as shown in Fig. 23.

Changes in the overall stress-strain relationship, e.g. as reflected in variations in the constants of $\sigma = Y_0 + A\epsilon^n$, would thus have marginal effect on the LD. This is illustrated by equating the squeezing deformation to a flow through a frictionless die converged into a resultant rectangular slab (Fig. 24). The process emulates the squeezing of the flange in deep-drawing, aside from the bending/unbending operations. Changes in n would essentially only raise the entire curve (the $\overline{\sigma}$ coordinates) rather than change the critical strain.

Deformation *type D-6*, blank squeezing, is the central activity in cupping and basic analytical models derive drawability by *approximating* its share in the overall drawing work or drawing force ([Hill], [White], [Backo], [Slate], [Elseb], [Hosfo], [Dodd]). Later stage refinements introduce other elements of the drawing process, such as: bending, unbending and frictional effects in deep-drawing to explain deviations from the idealized result. A (relatively) complete analysis of flat cupping, which considers those components was carried out by Chung and Swift in 1951 ([ChungSE], [ChungSA]).

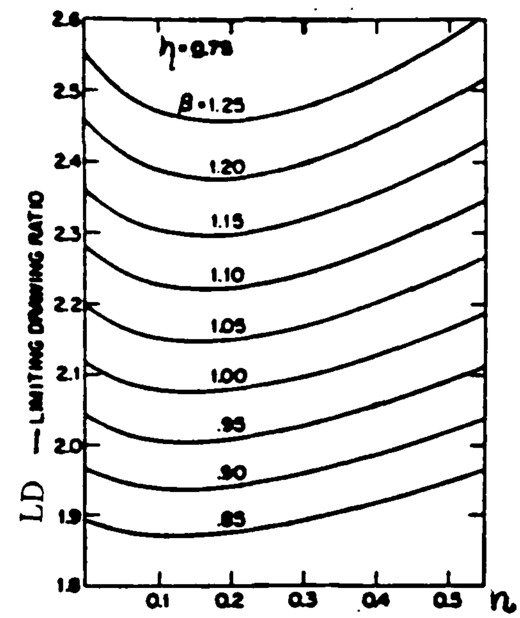


Figure 3-23. Calculated LD for various n and β values, for: $\eta = 0.75$, ([Hosfo81], Fig. 4)

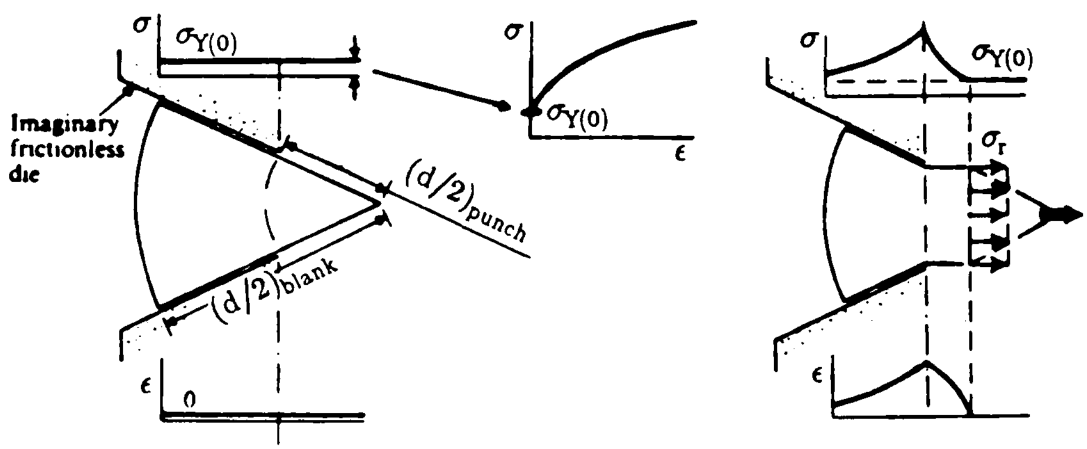


Figure 3-24. Variation of strain and flow-stress in nonsteady squeezing ([Backo], Fig. 11.4)

For the purpose of verifying drawing limits, the following approximations are assumed:

- $d_{punch} \simeq d_{cup} \simeq d_{die\ throat}$,
- $r_{die\ fillet} \simeq r_{flange\ recess}$, and
- $r_{punch\ fillet} \simeq r_{wall\ recess}$.

The equilibrium equation from which analytical models start, takes the radial forces acting on an element in the drawn zone of the flange,

Eq. 13. $$\frac{d}{dr}(t\,\sigma_1) + \frac{t}{r}(\sigma_1 - \sigma_3) - 2\mu\sigma_2 = 0\ .$$

where the terms are explained in Fig. 25.

Other commonly used simplifying *assumptions*, which are largely corroborated experimentally are:

1. Deformation *type D-6*, can be approximated to a plane-strain deformation in spite of the thickening of the blank towards the rim.

2. Ideal lubrication conditions between the cup and the tool survive in spite of heat and pressure changes, i.e. zero friction at the flange and sufficiently high friction at the punch face and bottom to prevent sliding.

3. Principal stresses, i.e. radial drawing stress (σ_1, σ_r), thickness stress (σ_2, σ_θ) and circumferential stress (σ_3, σ_h), appropriate to an isotropic material, are valid for anisotropic material too.

4. Bauschinger effects are negligible.

5. On balance, the surface area remains constant, i.e.: wall thickness changes balance each other.

6. The entire blankholding force acts on the rim of the blank.

7. The work performed by the noncompressive forces (bending, unbending, flange-friction and stretching and/or axial displacement against friction) can be estimated to be a fraction, η, of the overall work with η commonly equated to ≈ 0.75.

8. The conicity in vertical cupping due to clearance between die and punch-stem is negligible.

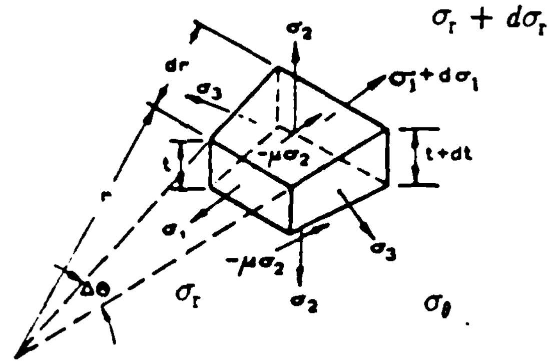


Figure 3-25. Stresses in an element of a squeezed flange (after [JohnsMe] 11.18)

9. The effects of friction and bending and unbending are additive.

10. A suitable $\bar{\sigma}$–$\bar{\epsilon}$ relationship is given by: $\bar{\sigma} = \bar{\sigma}_0 + B\bar{\epsilon}^n$ or some variation of this equation.

3.2.4 Limiting Draw Ratio

The experimentally validated fact that blanks can be drawn to a certain limiting depth, and that the amount of blank squeezing is limited, has received extensive analytical attention. Simplifying models attempted to determine the Limit Draw ratio (LD) by reducing the deformation to blank squeezing only. Analyzing deformation *type D-6* as a plane-strain one, leads to using the Levi-Mises equation $\{\sigma_h = 1/2\,(\sigma_r + \sigma_\theta)\}$ where σ_h must be compressive, i.e. $\sigma_h < 0$.

From these conditions, Hill ([Hill], 1950) derives a lower bound on the LD of

Eq. 14. $ln\dfrac{d_{blank}}{d_{cup}} > 1/2 \qquad \text{☞} \quad LD > \sqrt{2.718} \quad \simeq 1.67 .$

As shown in Fig. 25, compressing a sector of element #5 causes a slab of pitch-radius d_0 to shrink to a thicker ring, of pitch-radius d_f. The resultant strain becomes:

Eq. 15. $\epsilon = ln(d_0/d_f)$ ☞ $ln(LD) \simeq \epsilon_{max}$ ☞ $ln(LD) \simeq d_{blank}/d_{punch}$.

Hill ([Hill]) shows that for an isotropic material, the Tresca yield criterion and the Levi-Mises flow rules, instability occurs at the *initiation* of the process under *uniaxial* tension in the wall, for an LD = 2.718. However, common practical LDs are in the range of {1.9 to 2.2}. The assumption that instability occurs at the start of the deformation does not agree with experimental evidence which shows it to occur at some later stage. For a non-work-hardening material it is obvious that the largest allowable LD is reached when necking at the weakest link, - seemingly point D (of Fig. 7) - occurs; in such materials, $\sigma_U = \sigma_T$. Thus

Eq. 16. $\sigma_{(w)} = \sigma_T$.

This relationship has been adopted by models assuming instability to occur at point D under *uniaxial tension* ([White], [Hosfo], [Backo]). Since the wall only transmits the resultant stress at point C, the instability load at point D is equal to the radial drawing stress,

Eq. 17. $\sigma_{\text{point C}} = \sigma_r = \sigma_{(w)}$.

The principle of minimal dissipated work in homogeneous deformation under plane-strain conditions implies that

Eq. 18. $\epsilon_{max} = \sigma_{(w)} / \sigma_{(f)}$.

Since $\sigma_{(w)} / \sigma_{(f)} = \beta$, ☞ $ln(LD) = \beta$, for isotropic non-work-hardening materials $\beta = 1$, which yields Hill's upper-bound of LD = 2.718 . β can be related to the more familiar R, using either Hill's theory for radially symmetric sheet metal properties ([Hill]) by,

Eq. 19. $\beta = \left(\frac{R+1}{2}\right)^{1/2}$

or as an experimental approximation ([Hosfo81]) by,

Eq. 20. $\beta = \left(\frac{2R}{R+1}\right)^{0.27}$.

where "R" denotes any combination of R_θ, including $\bar{R}$. Introducing the efficiency, η, defined here as $dW_{(f)} / dW_{total}$ one obtains, $ln(\text{LD}) = \eta\beta$. For fairly isotropic materials, practical LD values are in the vicinity of 2.2, which yield $\eta \simeq 0.77$. This result can be reversely used to assess the magnitude of "redundant" work and forces.

The dependence of LD upon R (or β) has been validated experimentally. Whiteley ([White]) showed that changes in R may increase LD's by up to 10%. This is implied in the above stated relationship between LD and R (**Eq. 20**), where $d(\text{LD}) / d\text{R} \simeq 0.15$ for the range $\{R_\theta \leq 3\}$. A computed dependence of LD upon $\bar{R}$ is shown in Fig. 26. Hence one way of enhancing LD is to increase R. R can be modified through control of ***grain texture***. For example: a $\{111\}$ alignment in the rolling plane upgrades an alloy to a ***deep-drawing quality grade*** ([Hosfo]).

El-Sebaie, Mellor and Parmar ([Elseb], [MelloPa], [Mello]) hypothesize that instability in the cup, prior to the occurrence of necking in tension, occurs at point D under ***plane strain*** tension, rather than ***uniaxial tension***. The cup is stretched over the die profile but further hoop strain is prevented, once the material reaches the punch stem. This criterion has been used by Yamada, Moore and Wallace, Chiang and Kobyashi, and Budiansky and Wang[14] but the results did not agree with experiments. Employing Ludwik's $\bar{\sigma}$–$\bar{\epsilon}$ relationship, they found for the critical punch loads:

$$\textbf{Eq. 21.}\quad F_{critical} = \pi \, d_{cup} \, t \, (n^n) \left(\frac{1+R}{(1+2R)^{1/2}} \right)^{n+1} \exp\left(B \frac{(1+2R)^{1/2}}{1+R} - n \right).$$

LDs are determined by comparing the computed $F_{critical}$ values with tabulated radial drawing loads. Theoretical predictions obtained by this method though much larger than experimental LDs (Fig. 27), show significant dependence upon R-value and almost no dependence upon n in the most applicable range of [0.2-0.5]. Higher LD values as a function of n-values are predicted if the fracture is moved from point D to point E. This may be obtained by restricting plastic flow in the sheet at its contact with the punch. Such application is implemented in rubber-forming, hydro-forming and hydro-mechanical-forming.

14. see ref. list in [Elseb]

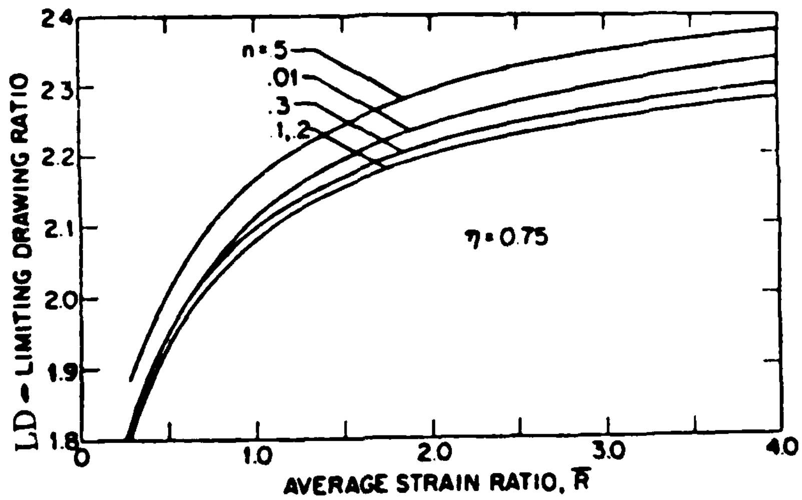


Figure 3-26. LD as a function of $\overline{R}$ for several n values, with η = 0.75 ([Hosfo81], Fig. 8)

Dodd and Atkins ([Dodd]) arrive at the ratio of the flow stress in the wall to that in the blank using Hill's new yield criterion for plane strain conditions, i.e.,

Eq. 22. $|\sigma_1 + \sigma_2|^m + (1+2R)|\sigma_1 - \sigma_2|^m = 2(1+R)\ \sigma_U{}^m$.

by taking the β ratio :

Eq. 23. $ln(\mathrm{LD}) = \beta = \dfrac{\sigma_{(w)}}{\sigma_{(f)}} = {}^1\!/_2 \left((1+2R)^{\frac{1}{m-1}} + 1 \right)^{\frac{m-1}{m}}$.

The resultant m-and-R dependent LD's are shown in Fig. 28.

As for the *stretching* mode, where local necking leads to tensile failure at σ_U, a combined analytical-experimental prediction of LD is proposed. Assuming an exponential $\overline{\sigma}$–$\overline{\epsilon}$ relationship, the maximum allowed strain at failure is $\left\{ \epsilon = n \right\}$. At each stage of the stretching, the sum of the natural strains is

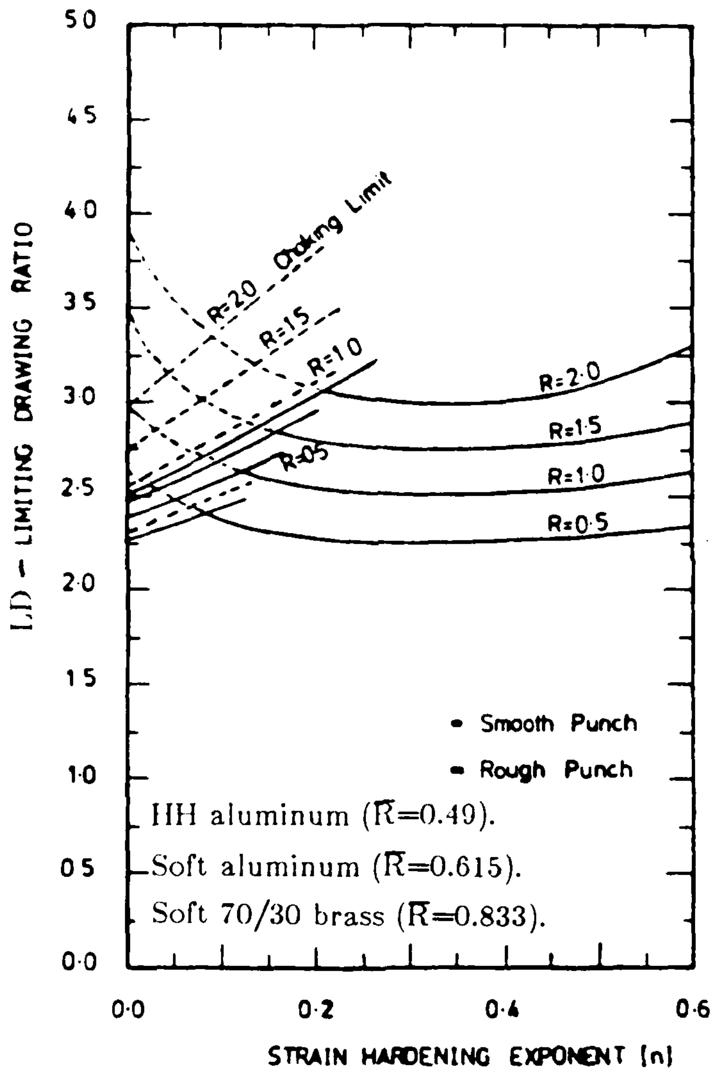


Figure 3-27. Experimental results: variation of LD w.r.t. n and R (after [Elseb], Fig. 13)

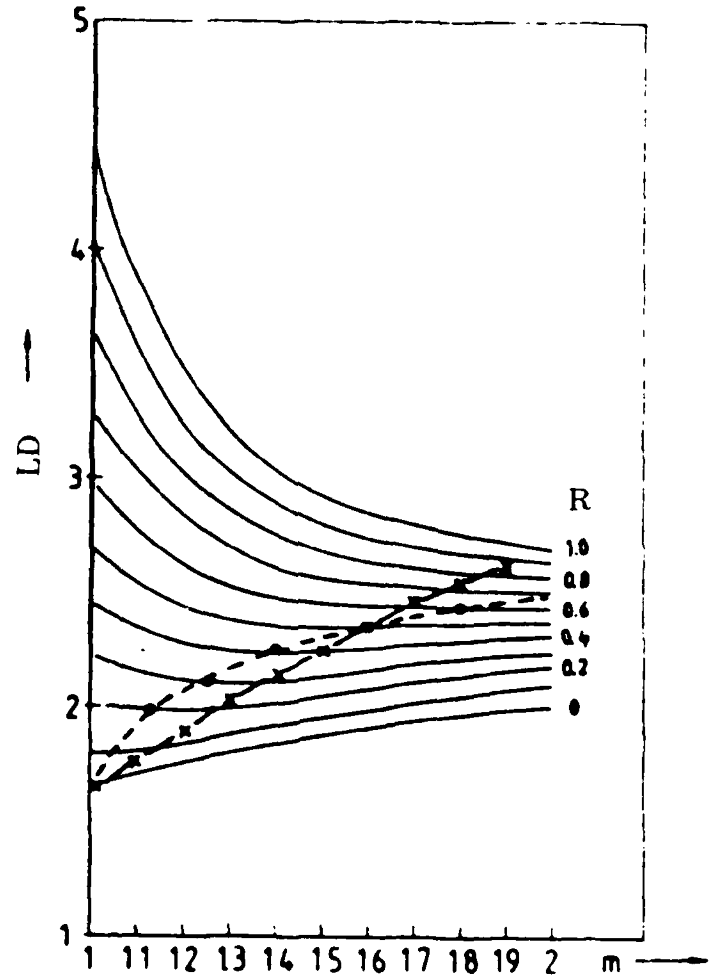


Figure 3-28. LD as a function of m and R. The dash-dot line shows the locus of minima for $R \leq 0.6$. Above the dash-cross line, all solutions are anomalous. (after [Dodd], Fig. 2)

zero; i.e. $\left\{\epsilon_{r_{sphere}} + \epsilon_{\theta_{dome}} + \epsilon_t = 0\right\}$,

and symmetry considerations lead to $\left\{\epsilon_{r_{sphere}} = \epsilon_{\theta_{dome}} = -1/_2\ \epsilon_t = 0\right\}$.

At σ_U, LHR (limiting height to diameter ratio) can be derived from the predicted thickness strain by preserving volume constancy and expressing $\epsilon_{r_{sphere}}$ as a function of LHR_{dome}, or rather by the more practical measure: limiting height ratio of a spherical element (LSR): LSR = Limit h_{dome} / d_{dome}.

The above analysis presumes that LD will increase with increasing R and n values and decreasing m values. In practice this is not entirely true. Usually a larger R coincides with a larger ΔR and larger ΔR causes excessive *earing*, which can become a major defect. Excessive earing is discussed later along with other defects.

In the combined drawing-stretching of stampings, LD is determined by the relative drawing mode: stretching brings in m and n to be the dominant variables while drawing introduces $\overline{R}$.

Ultimate Strain

The ultimate limit to multi-pass drawing, i.e. the maximum compression any portion of the blank can sustain before having to undergo recrystalization, is derived from the stress strain curve. A *uniform deformation* analysis that takes into account only the initial and the final shape of the drawn cup, will produce a *lower bound* of the ultimate "squeezing" strain. Assuming an exponential stress-strain relationship, the ultimate compressive limit in terms of natural strain, ϵ_U, has to satisfy

Eq. 24. $|\lfloor \epsilon_U \rfloor| = |n|$. Since UE is defined as $\lfloor \epsilon_U \rfloor$ meaning that UE denotes a lower bound of the ultimate compressive strain, equation #24 becomes:

Eq. 25. $|\mathrm{UE}| \leq |n|$. The lower bound stems from the fact that the above does not take into account the history (path) of deformation.

UE is always computed with regard to the portion of the blank from which the examined deformed zone of the cup was drawn. Since in every deformation zone the orifice of the cup undergoes the greatest compression, it is sufficient to check if UE at the orifice does not exceed ϵ_U. UE at the orifice of the deformation zone can be easily found as

$$\textbf{Eq. 26.}\quad UE = ln\, \frac{d_{\text{blank-area}_{\text{deformation-zone}}} - d_{\text{orifice-of-cup}}}{d_{\text{blank-area}_{\text{deformation-zone}}}}\ .$$

3.2.4.1 Defects

Defects imply that the drawing of a cup has been completed but that the finished shape has some undesirable features in terms of geometry and/or mechanical properties. There exists some overlap between some defects and failures, especially those of the buckling type. The former are distinguished from the latter functionally and physically. Functionally, a failure in one cup may constitute only a defect in the other. If the failure occurs in that part of the cup that is not designated for use it becomes a defect. Physically, defects may be rectified. For example an "orange peel" crest may be machined away and "excessive earing" trimmed. Defects do not include tearing, since tearing signifies an incomplete draw. Overthinning in *drawing* is considered a boundary tearing failure, and as such should be dealt with in the LD part. Thinning in *stretching* is a design parameter, and as such will not be dealt with as a defect.

The defects fall into four main categories:

i defects due to buckling, e.g. wrinkling, puckering (Fig. 20),
ii defects due to asymmetrical flow, e.g. earing (Fig. 20),
iii surface defects, e.g. "orange peel" (Fig. 20),
iv distorted geometry in the unconstrained state.

Buckling Defects

Wrinkling and *Puckering*

Experience gathered over years by many researchers[15] shows that wrinkling

severity depends upon some relative wall thickness measure. [Eary] classifies it into four categories on the basis of the *wall thickness ratio* - TR. Their classification is synthesized into Table 4.

The classification of Table 4 is not the only version of wrinkling classification. [Lyman4], for example, identifies sheets thinner than 0.032", as liable to wrinkling.

Wrinkling can be approximated as a form of buckling of an unstable beam. The thickness of the "beam" is the instantaneous blank thickness and the length is its instantaneous blank diameter or a portion thereof. The thicker the flange the less susceptible it is to wrinkling. Eventually, thick flanges may not wrinkle even in the absence of a blankholder. After a modification of Eary's approach above, other experimental evidence points to Flange to Wall-Thickness ratio (FTR) - FTR = t_{flange}/f as the significant wrinkling parameter. [Lyman4] mentions that, based on experience, no holddown force is required for FTR < 3. It was shown analytically, by Senior in 1956[16] ([JohnsMe] and [Slate]) that the onset of wrinkling, in holddown-free drawing, occurs in the range:

Eq. 27. $$0.46\,\frac{t_0}{d_{blank}} \leq \frac{\sigma_\theta}{E_{buckling}} \leq 0.58\,\frac{t_0}{d_{blank}}$$

σ_θ is the induced hoop stress,

$$E_{buckling} = \frac{4\,E\,b}{\left(\sqrt{E} + \sqrt{b}\right)^2}$$ and

b is the slope of the true-stress - natural-strain curve.

Thus, the region safe from wrinkling is: $\{\, 0.58\frac{t_0}{d_{blank}} \leq \frac{\sigma_\theta}{E_{buckling}} \,\}$.

Yu and Johnson ([Yu]) developed a two dimensional buckling model of an

15. See: Crane *ibid*, [Eary].

16. Senior, B.W., "Flange Wrinkling in Deep-Drawing Operation", *J. Mech. and Phys. Solids*, Vol. 4, pp. 325, 1956.

TABLE 3-4. Classification of wrinkling by Thickness Ratio ([Eary], p. 145)

Categories of wrinkling severity			
Name	Thickness Ratio	Use of blankholder	Comments
Very Thin	TR < 0.005	indispensable	Severe wrinkling. Compressive loads must be reduced, → lower LD's.
Thin	$0.005 \leq TR \leq 0.015$	necessary	Low blankholder forces. Regular LD's require double-action dies.
Moderate	$0.015 \leq TR \leq 0.025$	sometime can be done without	Lower LD's may employ single-action die.
Thick	$TR \geq 0.025$	not necessary	Lower LD's may employ single-action die.

elastic-plastic annular plate to improve on the value for the onset of buckling obtained by Senior. The results enable one to compute the pressure required to prevent wrinkling, as well as to modify the number of resultant waves (not elaborated here).

Earing

Earing shows asymmetric flow. In axisymmetrical drawing it derives from planar anisotropy (ΔR) and is schematically shown in Fig. 29.

ΔR can also be useful in box-shaped drawing. A recent analysis of earing ([Emani]) concludes that the plastic flow of anisotropic sheet can be regarded as the sum of two *superimposed* deformation processes occurring simultaneously: axisymmetric normal flow controlled by normal anisotropy, and asymmetric flow due to planar anisotropy. The analysis predicts the number of *troughs* (and crests) and the difference between the maximum and minimum strain as a function of the LD. It may be further refined to render formulae for practical application, provided that the designer can define an upper bound earing specification.

Residual Stresses and Springback

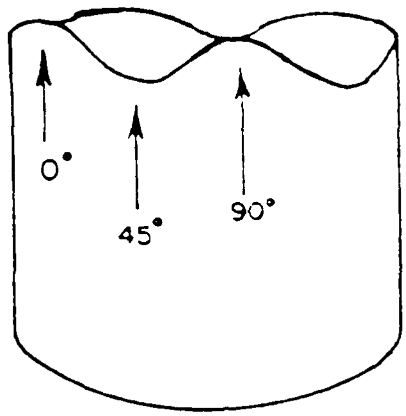


Figure 3-29. A typical 4-ear alignment due to planar anisotropy ([HobbsL3], Fig. 9-6)

Springback is especially important in the context of dimensional accuracy. Some springback is caused by residual elastic stresses, especially in the flange and punch-fillet bend: it will always exist and affects the geometry of the drawn cup once it is not constrained by the punch. Springback becomes, however, a major problem when the tensile force in the bottom is not sufficient to cause yielding throughout the entire cross-section, including the punch-fillet bending zone. As pointed by Duncan and shown in [Hosfo], (§ 15-6), the latter type of springback is avoided if:

Eq. 28. $\sigma_U/Y > e^{\mu\alpha}$ where α is the bend angle, in radians.

The ratio $\{\sigma_U/Y\}$ is small in high-strength steel and aluminum alloys, thereby making springback a factor to be taken into account in drawing these materials.

3.2.4.2 Empirical Drawability: Forming Limit Diagrams, Cupping Tests

Since analytical prediction of the onset of localized instability, even for simple drawing, is complex, difficult, and only partially developed, ***empirical*** tools are used in the attempt to satisfactorily predict drawing limits. A notable early numerical analysis that defined formability as a function of the relative reduction and relative thickness of the flange, was carried out by

Wood *et al* in 1961 ([Wood]). The most common empirical tools are the *forming limits diagram* - (FLD, "Keeler-Goodwin"[17] diagram) and *cupping tests*.

Cupping Tests

As noted above, simplified analytical models idealize the deformation regime. The presence of *stretching* in actual drawings substantially changes the characteristics of the deformation. Other process parameters and material properties that are ignored in the ideal drawing model may assume special importance under certain conditions. These include: the Bauschinger effect, the instantaneous values of friction along the entire contact area and effects of thickening of the blank edge. In the end, analytical models still fail to give a satisfactory correlation with experimental results and drawability in industrial practice. Thus, another means of predicting drawability was attempted: *cupping tests*. The most frequently used tests are *Erichsen* and *Olsen* tests. Both simulate the drawing of a sheet between two polished blocks and use the resultant height of cup as a LD index. But these tests do not furnish satisfactory consistency. The tests simulating cup drawing, carried on by Meuleman ([Meule]) also displayed a considerable scatter in results. A more recent test devised by Hecker[18] uses a nearly idealized *stretching* test to predict LDs and incorporates m and n values. The results of this test demonstrate a high correlation with *total* elongation - the sum of the uniform plastic elongation which includes the *post-necking* regime. Ghosh[19] showed that post-necking elongation indeed depends upon m and this test may furnish better correlation.

As noted above, actual drawing involves stretching modes, to some extent. Several tests were designed to assess performance during the combined drawing-stretching mode. The *Limited Dome Height Test* ([HobbsL3]) and the

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17. Keeler, Goodween, *ibid.*
18. S. Hecker, *Met. Eng. Q.*, 14, No. 4, p. 30, 1974.
19. A.K. Ghosh, Plastic Flow - Localized Necking, in: *Mechanics of Sheet Metal Forming*, ed. D.P. Koistinen and N.M. Wang, Plenum Press, 1978.

Automated Hydraulic Bulge Test[20] simulate plane strain conditions through the drawing-stretching of a thin dome. In it, the width strain at fracture is measured. In the *Fukui* test a conical cup is drawn by a standard conical 15° half-angle punch and its failure is used as a formability measure.

Forming Limit Diagram

FLD's have become an extensively used tool ([Hosfo], [Nagpa79]) in predicting drawability. Basically, FLD's avoid the limitations of the analytical models by considering resultant observations only. If for each process, material, and operational parameter, a large number of failures (tears and bucklings) are examined, a curve which establishes the "safe" boundaries of strain can be drawn. A typical FLD is shown in Fig. 30.

Since one major stress in drawing is always tensile, the FLD shows that if the minor hoop stress is tensile too, thinning occurs. Otherwise, if the hoop stress is compressive, combinations in which thinning would not occur, or even thickening may occur, are possible. If both stresses are compressive the sheet will *buckle*. When the operating strains intersect the FLD, a failure occurs. The overall curve is *altered* with changes in n and wall thickness as shown in Fig. 31. Hence, a factoring formula can produce new FLD's from given ones; the diagram in Fig. 32 does this for the changes of n and t only.

Since the FLD has been introduced (Keeler[21]), the drawability of many materials has been measured and incorporated into it (Anderson[22], [Hecke77]). The shape of the diagram can be well represented as a piecewise linear curve (not much accuracy is lost as the curve is a best-fit line) and the factoring formula, as in Fig. 33, makes it a generalized tool, i.e. applicable to a variety of blank sizes.

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20. Young, Bird and Duncan, An Automated Hydraulic Bulge Tester, *J. of Applied Metalworking*, Vol. 2, No. 1, p. 11-18, 1981, *ibid*.

21. Keeler, 1962, *ibid*.

22. Andersen, B.S., "A Numerical Study of The Deep-Drawing Process", in *Numerical Methods In Industrial Forming Processes*, ed. J.F.T. Pittman, R.D. Wood, J.M. Alexander, O.C. Zienkiewicz, pp. 709-721, Pineridge press, U.K., 1982.

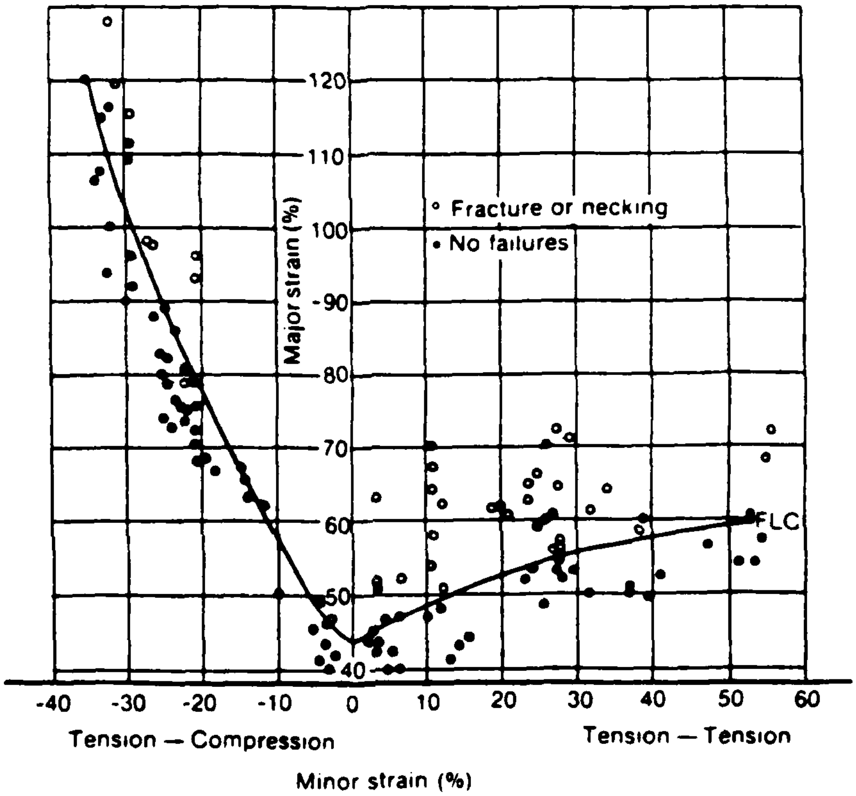


Figure 3-30. A typical forming limit diagram ([Hecke75], p. 671)

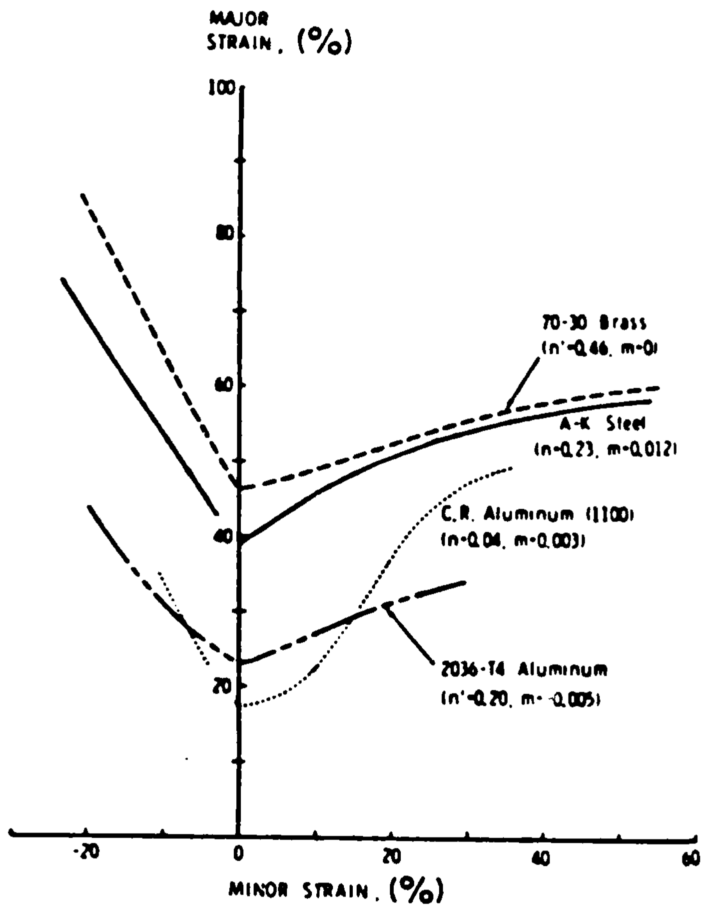


Figure 3-31. Changes in FLD as a function of n and t ([Ghosh]).

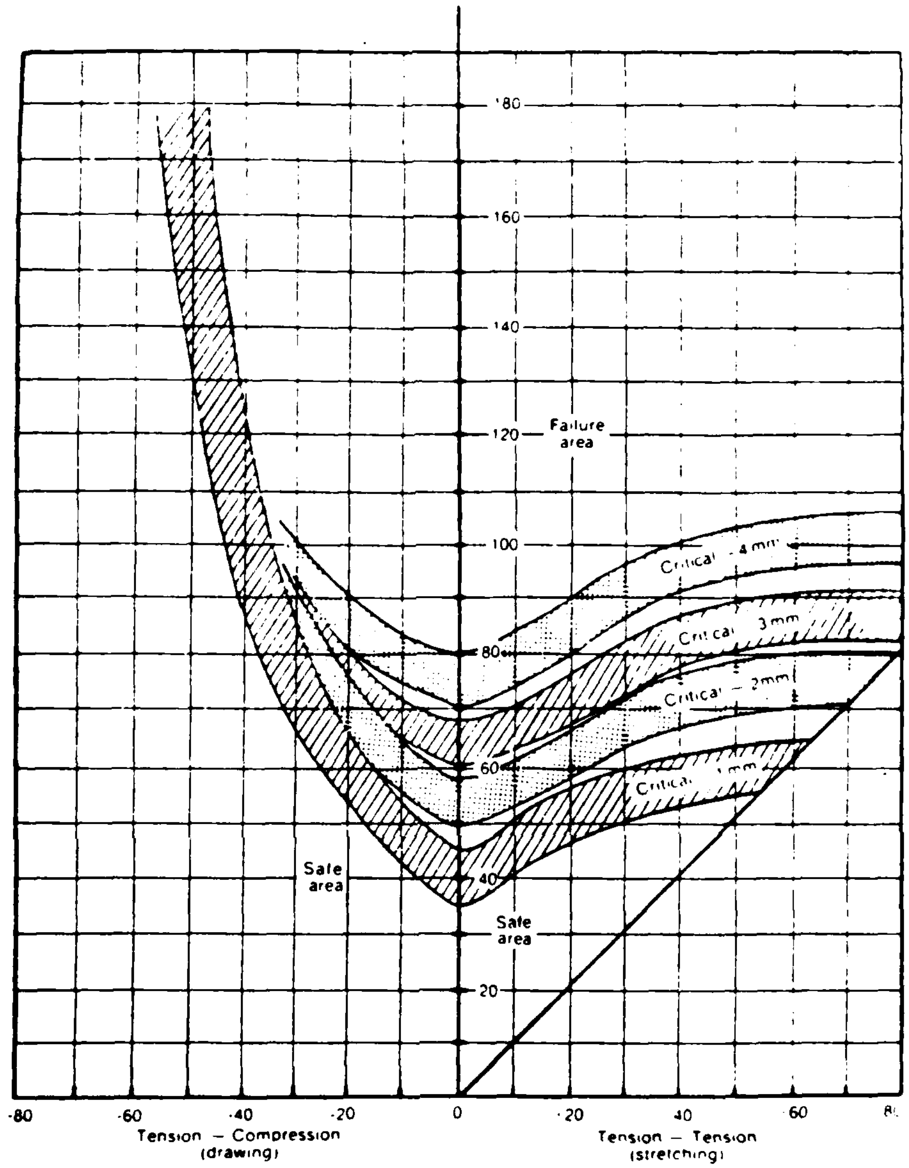


Figure 3-32. Changes in FLD as a function of wall thickness ([Hobbs12], Fig. 12-7)

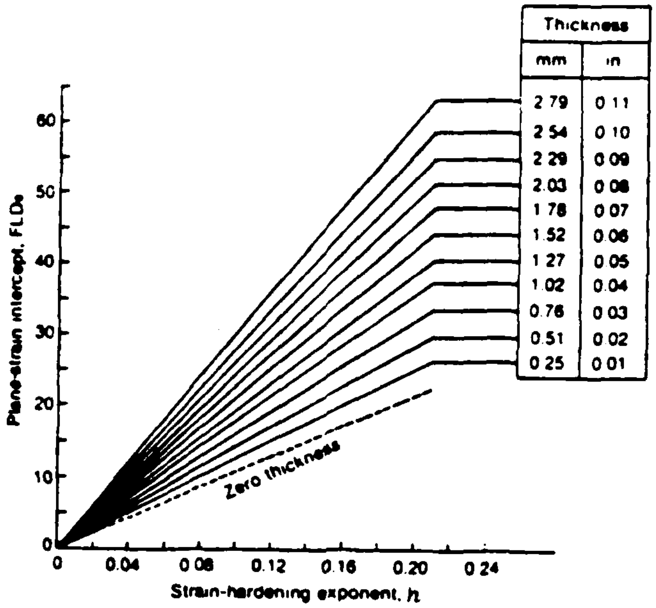


Figure 3-33. Effect of wall thickness on position of FLD ([Hobbs12], Fig. 12-8)

3.2.5 Factors Affecting Drawing Limits and Defect Development

To decide upon drawing limits, a decision must be made as to what constitutes a defect-free product, should a defect develop in the last stages of the draw, or a failure occur. For the purpose of obtaining an acceptable cup, we may stipulate that no *major* defect can be allowed, regardless of its type and location. Here *major defects* do not include surface finish like "orange peel" and "excessive" residual stresses ("excessive" should be defined as well[23]).

The previous discussion was concerned with boundaries to drawing-limits and defect-development in terms of *plasticity variables* ($Y_{instantaneous}$, $\bar{\sigma}$, etc.). These plasticity variables are decided by the external drawing force, the strain path and material properties. The strain path and the plasticity are

23. Residual stresses may cause corrosion in some alloys, e.g. brass, dimensional changes, etc.

determined by the *deformation variables*, i.e. the material ($\bar{\sigma}$–$\bar{\epsilon}$ relationship, σ_U and R, etc.) and the geometry (r_{die}, r_{punch}, D and θ, etc.). The *operational parameters* are the cause of the stresses induced throughout the workpiece. Both the *operation parameters* and the *deformation variables* determine the resulting plasticity variables. Since feasibility is determined in terms of plasticity variables, it is imperative to identify the degree of the effect of various operational parameters and deformation variables on it. For this, ranges of values of operational parameters and deformation variables where *safe* drawing can be executed, (if indeed such ranges do exist), are of special importance. The following section summarizes these factors and their ranges.

3.2.5.1 Operation Variables

Blank holding

Blankholding (*holddown*) principally aims at preventing *wrinkling*. The two methods used for blankholding are: *clearance blankholding* (fixed blankholding) and *pressure blankholding* (Fig. 34). *Clearance blankholding* maintains a fixed clearance which may resist anticipated thickening at some stage of the drawing. Early work by Swift (1939) showed that a 5% clearance is practically sufficient to resist wrinkling but does not avoid development of a stretching regime. *Pressure blankholding* can provide a varying blankholding force and, at the same time, restrain some of the thickening of the rim. Since some thickening would always take place, and increasingly towards the outer rim, most of applied blankholding force acts at that rim. *Pressure blankholding* requires a double-action die and is not necessarily integrated in a double stroke press.

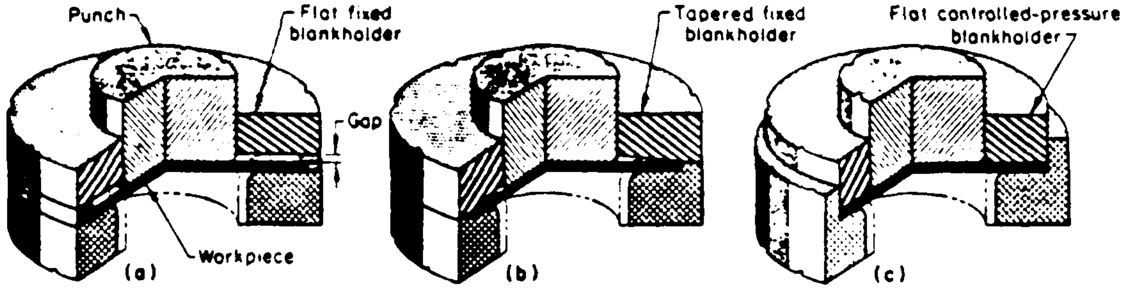


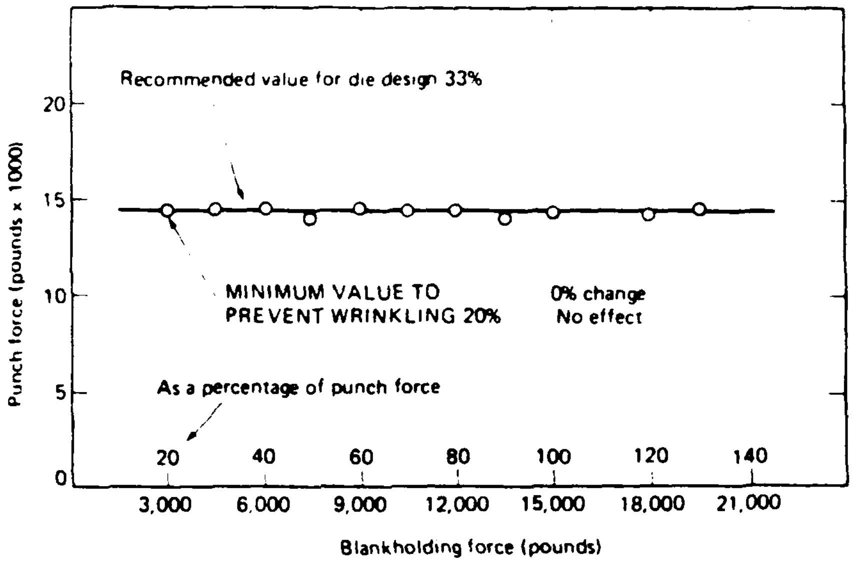
Figure 3-34. Schematic blankholding methods ([Lyman4], Fig. 22)

Since in non-stretching drawing it is desirable to facilitate a free movement of the blank edge, lubrication between the blank and the blankholder should be good and the contribution of blankholding force to punch force should be minimal. Experiments show that by controlling friction this desirable outcome can indeed be achieved, see Fig. 35.

The precise value of a blankholding force which should prevent wrinkling, is treated currently as an empirical matter. Analytical models (seen in the wrinkling analysis above) are not yet suitable for shop usage. There are several methods of attempting to do this. The underlying approach is to specify the force as a fraction of the tensile strength (either Y or σ_U) or of the drawing force, depending strongly on the wall-thickness ratio of the blank. Typical examples are given in Rules #92 to #99.

Blankholding force directly affects the LD. The hold-down force produces a frictional force resisting the radial movement towards the die orifice, thus increasing the load acting on the wall. Consequently, the weak link in the wall, the boundary between the wall and the cup bend wrapping the punch rounding radius, will fail with lower punch force. For the ideal drawing regime, assuming minimum dissipated work in homogeneous deformation, under plane-strain conditions, the squeezing of the flange is summed up in equation #18. The presence of friction in the flange adds a non-drawing component to the effective stress in the wall. The modified limiting strain is therefore

Eq. 29. $$\epsilon_{max} = \frac{(F_{punch} - F_{flange\ friction})/Area_{(w)}}{\sigma_{(f)}} .$$



Blank size: 4.625 inch. diameter, 46% reduction, practically optimal drawing conditions.

Figure 3-35. Effect of blankholding force on punch force ([Eary], Fig. 122).

and the limiting drawing ratio, pertaining to the above ideal condition, becomes

Eq. 30. $LD = \exp(\,1 - F_{\text{flange friction}} \,/\, F_{\text{punch}}\,)$.

$F_{\text{flange friction}}$ is the friction force between the flange and the blankholder and die.

It is thus assumed that the relative reduction in the available LD, defined in equation #30, is valid as an upper bound for realistic drawing regimes too. This suggested modification has not yet been experimentally verified.

Friction

Good drawing practice aims to increase friction between the blank and the punch bottom and radius, and to minimize it at the blank and die-lip surfaces. Thus, lubricants with high *slip* properties are applied to the blank and die surfaces prior to drawing. Friction at the punch bottom and radius is

increased by increasing the surface roughnesses, and by applying high-pressure resistant lubricants. A set of experiments described in [Eary], (Fig. 36), demonstrates the role of friction; a change in lubricating compounds brought about a 10% change in punch force and a 50% change in the blankholding force. Friction variables are considered, as punch and die clearances, matters of fine-tuning design, rather than ones determining feasibility.

Draw Speed (strain rate)

Drawing speed, over a certain range, has almost no effect on the feasibility of a deep-draw. Practical drawing speeds fall within the range of a few tens to hundreds of ft./min.; it is assumed that initial contact does not cause any impact effects on the workpiece. An experiment discussed by [Eary], in which punch velocity was changed within the range { 40 ft./min. to 240 ft./min. } showed no significant changes in punch force or LD. However, at some intermediate speeds some defects did occur. For instance, at 160 ft./min. cups wrinkled badly at the top, and at 200 ft./min. some cups showed ripples in the side wall. Similar experiments, by Meuleman ([Meule]), corroborated the independence of LD of strain rate. A study by Avitzur ([Avitz77]) confirms analytically that when the material is not sensitive to strain rate effects, the ram force is independent of the ram speed. (It is possible, however, that the lubrication is affected by punch speed.) It is thus concluded that drawing speed and practical strain rate effects are matters the finer stages of design. Since analytical treatment of these parameters is rare, the effect of speed requires to be determined by trial & error procedures in the shop.

3.2.5.2 Deformation Variables

Material Properties

A general characterization of the effects of material properties has been presented in the previous sections. A detailed research into specific effects of material properties on drawability variables has been carried out at the University of Michigan, in 1980, by Meuleman ([Meule]). A summary of effects of material properties on deep-drawability, based upon that research and on [HobbsL3] is given in Table 5.

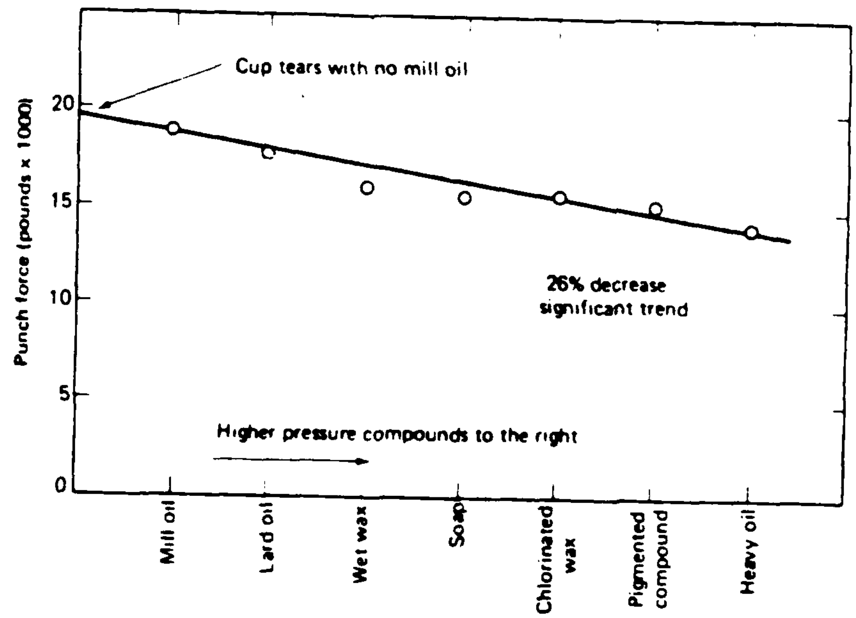


Figure 3-36. Lubrication effect ([Eary], Fig. 121)

Geometry

Punch Profile Radius

Chung and Swift's experiments ([ChungSE]) showed that punch geometry - i.e.: *punch fillet radius* (for brevity: *punch radius*, r_{punch}) is a major variable in determining LD. Strain analyses in the neighborhood of point **D** (Fig. 37) indicate susceptibility to tearing at that region with practically no effect on strains outside its immediate vicinity ([ChungSE]). In [HobbsL4] and [Eary] the empirical finding is that for $\{r_{punch} \leq 2\ t\}$ the cup is highly failure-prone due to tearing, whilst for $\{r_{punch} \geq 10\ t\}$ stretching may be introduced. The latter mode of deformation derives from the punch radius emulating a hemispherical-headed punch and, consequently, thinning is inevitable. In addition to this, it was found that within the region $\{4t \leq r_{punch} \leq 10t\}$ the exact radius does not significantly affect LD. (The data in Fig. 37 goes only to punch radius $= 8t$). Thus, unless the shape of the cup actually requires it, a sound design procedure would be to specify a punch radius in the range $\{4t$ to $10t\}$. The values elaborated in Fig. 37 reflect realistic boundaries: $4t$ is found to be a "safe" lower bound for carbon steels and $6t$ for stainless steels.

TABLE 3-5. Effects of material properties on axisymmetric deep-drawability

Material Properties & Axisymmetric Deep-Drawing			
Property	Deep-drawing mode	Stretching mode	Combined Deep-Drawing and Stretching
R	R↑ → LD↑ High correlation in carbon steels. Weaker in nonferrous metals (alloys).	R↑ → LD↓	R↑ → wrinkling-resistance↑.
ΔR	ΔR↑ → earing↑	no effect	wrinkles appear in {Min.ΔR} direction.
n	n↑ → LD↑ (ΔLD ≤ ≃5%), Considerable in nonferrous metals. Negligible effect in steels.	n↑ → LD↑	n↑ → LD↑ (ΔLD ≤ appprox5%), Combined with wrinkling resistance↓ & wall-thinning ↑.
σ_U	no effect	σ_U↓ → springback↓	σ_U↓ → required blankholding force↑ .
m (strain-rate)	m↑ → LD↑	m↑ → LD↑	m↑ → LD↑ .
$E_{buckling}$	no effect	no effect	$E_{buckling}$↑ → wrinkling-resistance↑ .

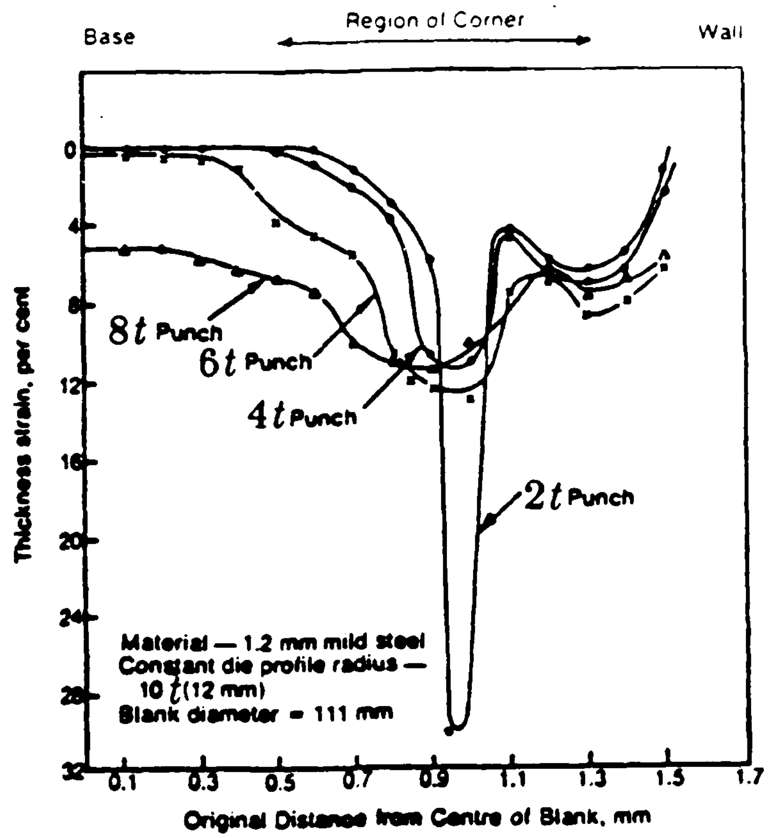


Figure 3-37. Effect of punch profile on LD and thickness strain ([HobbsL4], Fig. 4-19a)

Die Profile Radius

Variations in *die fillet radius* (for brevity: *die radius*, r_{die}) have three major effects:

1. The larger the bend radius the greater the punch load and the plastic work done in bending.

2. Small die radii may cause local failures in the bending zone, by increasing the work-hardening tendency.

3. The smaller r_{die} is the smaller is the interaction with the tools: smaller r_{die}'s cause a heat build-up, weakening of the die material and ultimately resulting in faster erosion of it. This also makes lubrication more difficult and galling more troublesome ([Eary]).

Increasing punch load increases the load the wall and its weakest link (point **D**) have to withstand. Thus, the smaller the r_{die} the greater the peak punch load and the lower is the LD. Analytic modeling of plastic bending of the sheet over the die radius is found in [ChungSA] and [Slate]. Slater's analysis assumes linear strain-hardening and approximates the mean yield to Υ. Assuming negligible changes in t, the additional stress due to plastic bending is found to be ([Slate], 9.86):

Eq. 31. $$\sigma_{bending} \simeq \left\{\Upsilon\, t\left[1+\left(\sigma_r/\Upsilon\right)^2\right]\right\} / \left\{\sqrt{2.3}\left(r_{die}+\frac{t}{2}\right)\right\}.$$

Experiments show, however, that *regions of success* rather than a quantitative function can be identified. Increasing the r_{die} too much would not significantly enhance the LD. Instead it would bring about a greater tendency to wrinkling, i.e. *puckering*. This defect is due to the interruption of blankholding support. A typical effect of the die profile on thickness strain is shown in Fig. 38.

Chung and Swift's experiments ([ChungSE]) established a safe region for drawing 4 inch diameter cups, see Fig. 39. Assuming that the latters' results can be generalized, the following can be deduced,

- $\{r_{die} < 2t$ or $r_{die} > 10t\}$ are highly undesirable.
- Within the range of $2t$ to $10t$, LD is affected by die radius on a nearly linear basis (synthesized from [ChungSe] results). Additional elaboration is given in the section on computation rules.

Radial Clearance

The clearance between the die throat and punch stem affects both the geometry of the cup and the flow regime. Geometry pertains to *conicity* and *roundness* of the wall. Excessive clearance can cause "square" corners instead of a toroidal profile around die radius. Taper, aside from geometrical implications, produces susceptibility to puckering, since the free tapered wall is not constrained by either die, punch or blankholder. Plasticity is directly affected by the control of thickening of the wall. Certain combinations of clearance and ensuing thickening will bring about *ironing*. At the boundary of ironing, insufficient clearance causes burnishing of the metal and surface finish

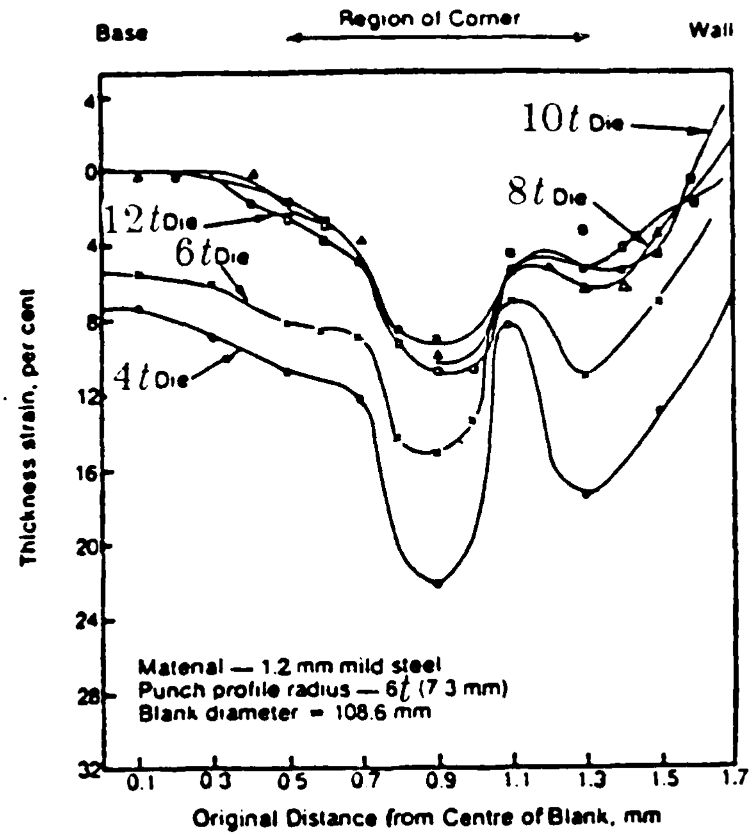


Figure 3-38. Effect of Die Profile on thickness strain ([HobbsL4], Fig. 4-19b)

defects.

Selection of the proper clearance depends upon the anticipated thickening and the degree to which burnishing is not wanted. In [JohnsMe] the recommended clearance, which is also quoted as common in industrial practice, is to leave a 30% for a drawing ratio of 2, otherwise, if ironing can be tolerated, 10% will suffice. [Lyman4] cites a general rule that a clearance of 7% to 15% of the wall thickness helps prevent burnishing, but redrawing operations generally require higher clearances. [Eary] formulates another design rule: the desirable clearance is the sum of a few thousands of an inch plus the expected thickening at the outlet of the die bend. This procedure requires computation of the anticipated thickening.

In the context of feasibility, radial clearance is considered a design element that would be dealt with in the second (fine) stage of process parameter design. It may affect deep-drawability only in limiting cases where excessive clearance,

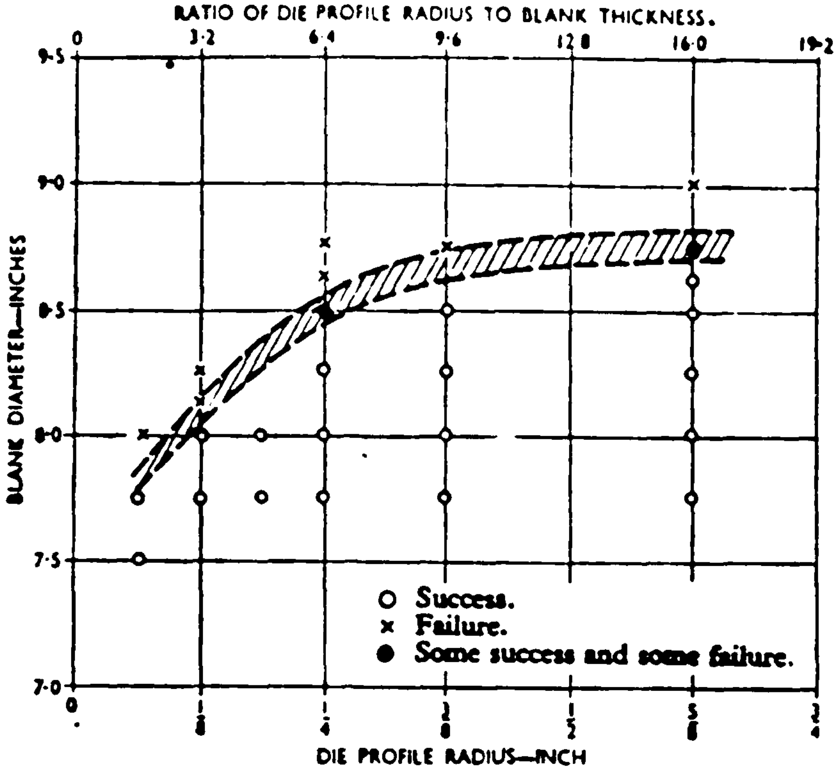


Figure 3-39. Effect of Die Profile on drawing capacity (after [ChungSE], Fig. 13)

compatible with anticipated thickening, will produce dangerous conicity and possibly puckering.

Degree of Bend, Tapered Shells

In vertical drawing the bend is 90°. For all practical purposes, when evaluating effect of degree of bend on deep-drawability, conicity produced by the clearance between straight-walled die and punch is ignored. Degree of bend becomes, however, a major factor in drawing conical cups. Here, the tendency of the unsupported material to buckle or pucker becomes a main design concern. It lowers LHR's by as much as 50% ([Jones], [HobbsL4]). These limitations have led to the use of modified deep-drawing processes or special sequences of redrawing for obtaining tapered cups. Variants of deep-drawing processes employ hydraulic pressure in fluid media and are not discussed here. Other analyses of concern such as the difference in bending and straightening forces and decreased strain-hardening due to a smaller

amount of plastic bending are small by comparison with the susceptibility to buckling introduced by conicity. Unfortunately, analytical and practical treatments of conical drawing are almost nonexistent, though some suggestions may be found in [Jones] and [HobbsL4]. In industrial practice a common measure of the particular difficulties which are introduced by conicity is *conicity severity* It may be used as a factor when drawability of vertical cups is sought. Conicity severity is expressed below (Rule #82) as the ratio between the LHR of a tapered cupping operation to the corresponding straight vertical cupping. Other salient design practices appear in the *design* and *rectification* rules sections.

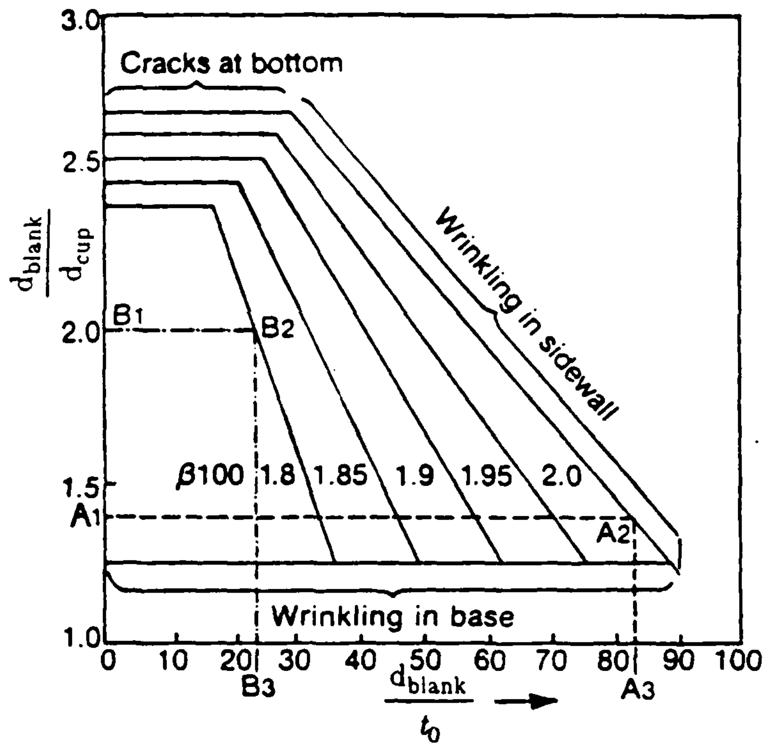
Wall-Thickness Effect on Drawability

The preceeding analyses treated instability in deep-drawing mainly as a plane-strain phenomenon. However, it is clear that this is only a simplifying assumption and, as relative thickness increases, deviations from the plane-state models increase. The above models do not take thickness stress gradient into account and should therefore undergo a modification when significant wall thickness and, consequently, a triaxial stress state is encountered.

It has been verified experimentally that forming limits exhibit a noticeable increase with increase in wall thickness ([Lyman4], Haberfield and Boyles, Panknin, Hobbs, Hiam and Lee[24], [HobbsL4]) Typical behavior in drawing *without* a blankholder is discussed by [HobbsL4], and is shown in Fig. 40.

Since thicker flanges are less susceptible to wrinkling, a smaller holddown force is required for them. Hence, the resisting friction force between the flange and the blankholder decreases with thicker flanges. This in turn allows higher utilization of press power and higher LD's. Increased wall-thickness also permits higher LRD's to be achieved in *redrawing* processes. The above

24. A.B. Haberfield and M.W. Boyles, *Sheet metal industries*, Vol. 50, p. 400, 1973.
W. Panknin, *Sheet metal industries*, Vol. 53, p. 137, 1976.
R.M. Hobbs, *Sheet metal industries*, Vol. 55, p. 451, 1978.
J. Hiam and A. Lee, *Sheet metal industries*, Vol. 55, p. 631, 1978.



β100 designates the LD of a 1-mm thick, 100 mm diameter cup.

Figure 3-40. Wall thickness effects on LD for drawing sheet steel *without* a blankholder (after [HobbsL4], Fig. 4-31).

rationale about the buckling limit being elevated is applicable to tube sinking mechanisms as well (see: redrawing, §2.6).

Several analytical investigations attempt to model the effect of cup wall thickness, (see list of references in [Rau]). The underlying approach is to take wall thickness into account by assigning an LD-correcting (or: LRD-correcting) factor. One recent example is the development shown by Rau and Chaturvedi ([Rau]) who incorporate the Marciniak-Kuczynski instability criterion to propose the following wall thickness correction factor:

Eq. 32. $$\frac{t_{\text{center-of-neck}}}{2\ r_{\text{neck}}} = A \left(1 - \frac{t_{\text{center-of-neck}}}{t_{\text{outside-neck}}}\right)$$

$$A = 2 \left(\frac{t_0}{t_{\text{characteristic inhomogeneity}}}\right)^2$$ and

r is the radius of curvature of the neck.

Application of the above expressions is still elusive because it requires the values of initial width of the inhomogeneity in the sheet and the characteristic of the ultimate fracture zone at the onset of necking.

3.2.6 Redrawing

Redrawing facilitates the production of deeper and narrower cups and/or stepped cups. If the first drawing operation cannot produce a cup which is deep, tapered, or hemispherical enough, because of encountering a LD, *redrawing* has to be employed. If the *first redraw* still can not produce the cup, a *second redraw* is employed, and so on. By utilizing redrawing, the compressive stresses are reduced due to the fact that the radial stress that generates them is smaller. Hence, the load that the wall has to transmit is lowered, too. Stepped or complex draws are obtained in a fashion similar to flanged cups in cupping.

Redrawing methods used in pressworking fall into two categories: *direct* and *reverse*. The principal tool alignments and displacements in each of these methods are schematically described in Fig. 41.

The reverse redrawing, shown above, eliminates two operations {bending + unbending}, thus requiring a smaller punch force, saving work and work-hardening the cup to a smaller degree. These advantages point to reverse redrawing being a more efficient and capable process than direct redrawing. Notwithstanding this, reverse redrawing is not so adaptable to large quantities, can handle only large bend radii and cannot produce stepped-to-one-side cups. Within direct and reverse redrawing, several variants are used. The variants differ from each other in the interim bending path the cup undergoes and the employment of supporting/constraining mechanisms. Diagramatic representations of methods of direct redrawings, demonstrating various bending and constraining mechanisms that produce differing flow regimes are shown in Fig. 42.

Investigating the comparative redrawing capability of the above methods [ChungSR] showed that method *d* yields the most favorable results; it has a

redrawing capacity higher by $\simeq 8\%$. This stems from smaller energy dissipation during bendings and unbendings (compared with methods *a* and *b*) and reduced resisting frictional force (compared with method *c*, in which the supporting sleeves increase frictional resistance as a function of blankholding force).

Redrawing reduces the thinning at the non-hardened portions of the drawn cup, i.e. at the bottom. This, in addition to decreasing the load the wall has to withstand, is another advantage the usage of redrawing brings in. Typical wall thickness changes in first redraws are shown in Fig. 43.

Experiments show that the effect of $\bar{R}$ values are the same as in cupping: high $\bar{R}$ values increase redrawing limits. As for other variables, significant differences are found:

1. Punch force in redrawing is of almost constant magnitude but shows an increase for work-hardening materials. Punch-force behavior is shown schematically in Fig. 44.

2. Limiting reductions in redrawing increase with decreasing n values, e.g. cold-drawn sheets have better redrawing ratios than the corresponding annealed ones. Aluminum is more suitable for redrawing than brass, although brass responds better to the first redraw ([ChungSR], [Hosfo]).

3. The contribution of bending and unbending regimes to the overall redrawing capability is of the order of the compression of the tubular part of the cup. In Fogg's experiments, the bending and unbending stresses accounted for 23% to 47% of the total stress for redrawing ratios of 1.14 and 1.6 respectively ([Fogg], p. 149). Thus, real redrawing analysis cannot assume a process that consists only of the tube compression mode.

4. Lowering initial strength does affect redrawing ratios. In [ChungSR] it is reported that interstage annealing increased redrawing ratio by $\simeq 10\%$ and resulting bottom thickness by 10% to 15%, with punch loads reduced by 25% to 40%. This is shown in Fig. 45.

5. Comparison with first stage drawing shows that the punch profile, above a certain critical value, has a marginal effect on the redrawing limits. The critical punch profile above which this finding is valid is $\simeq 2t$ only

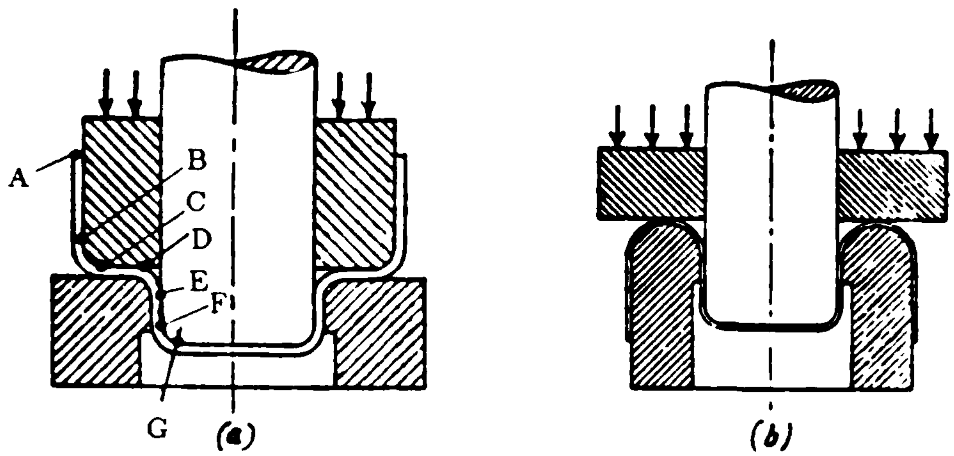


Figure 3-41. Schematic direct and reverse redrawing (after [ChungSR], Figures 1 and 2)

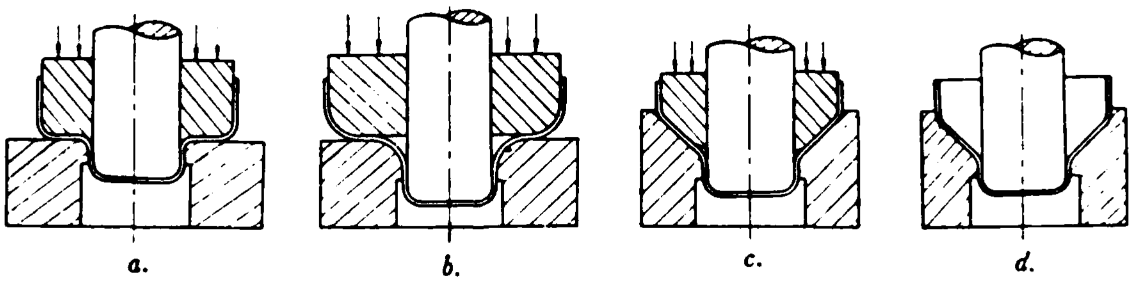
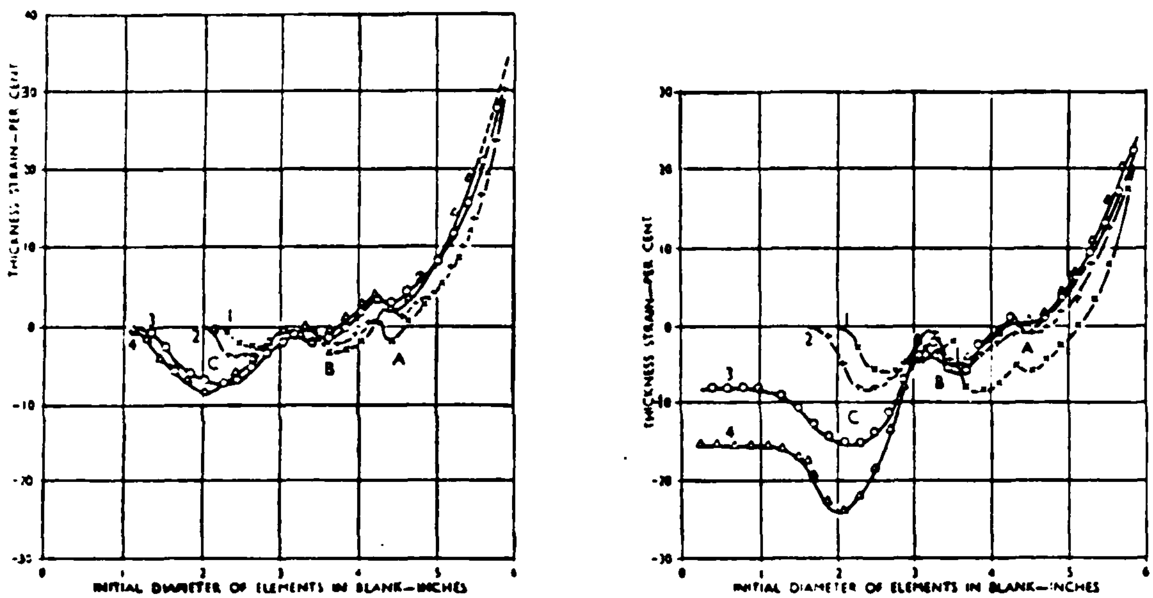


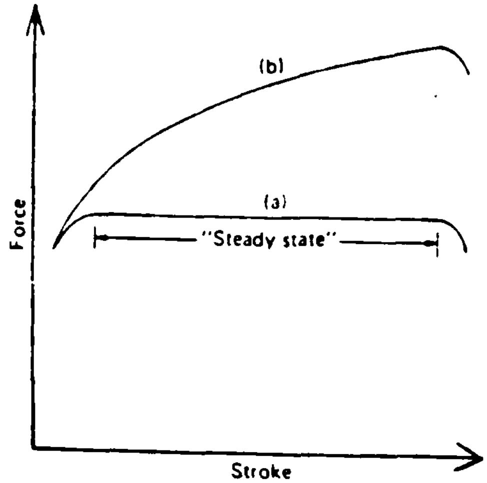
Figure 3-42. Direct redrawing methods: schematic apparatus (after [ChungSR], Fig. 1)



a. Reverse redrawing. *b*. Direct redrawing.

Mild steel cups redrawn with the following punch diameters:
1. 3.166 inch 2. 2.791 inch 3. 2.916 inch 4. 2.666 inch.

Figure 3-43. Effect of redrawing ratio on thickness strain curves in mild steel by direct and reverse redrawing methods (after [ChungSR], Fig. 19)



(a) non-workhardening material.

(b) workhardening material.

Figure 3-44. Schematic variation in punch force in redrawing (after [Hosfo], Fig. 14.14)

([ChungSR]).

Basically redrawing is viewed as a type of *tube-sinking* with an inward plug and superimposed intermediate bendings and unbendings, in the presence of resisting frictional forces. But unlike tube-sinking, redrawing is susceptible to failure in tension. The zones liable to necking are, as in the case of cupping, between the punch-radius and bottom of the wall, i.e. point F, or, to a lesser extent, point G (see Fig. 48). The capability of obtaining larger reductions through redrawing is based on reducing the load on the "weak links" of the cup in a pass. The reduction of the stress, which the "weak links" along the wall should withstand does not imply that the overall obtainable strain in power strain-hardening materials is increased. It should still follow the equation: $\epsilon_U = n$ ([Hosfo], 3-16).

If the interim zone in which the tube is reduced is not a part of the final shape, then an optimal redrawing configuration, which would determine the die angle (Figures 46 and 47) can be selected ([Fogg]).

For the first redraw, an analysis similar to that of cupping distinguishes two modes of metal-flow: *embossing* and *tube-sinking*, and seven deformation-type regions. They are illustrated schematically in Figures 48 and 49.

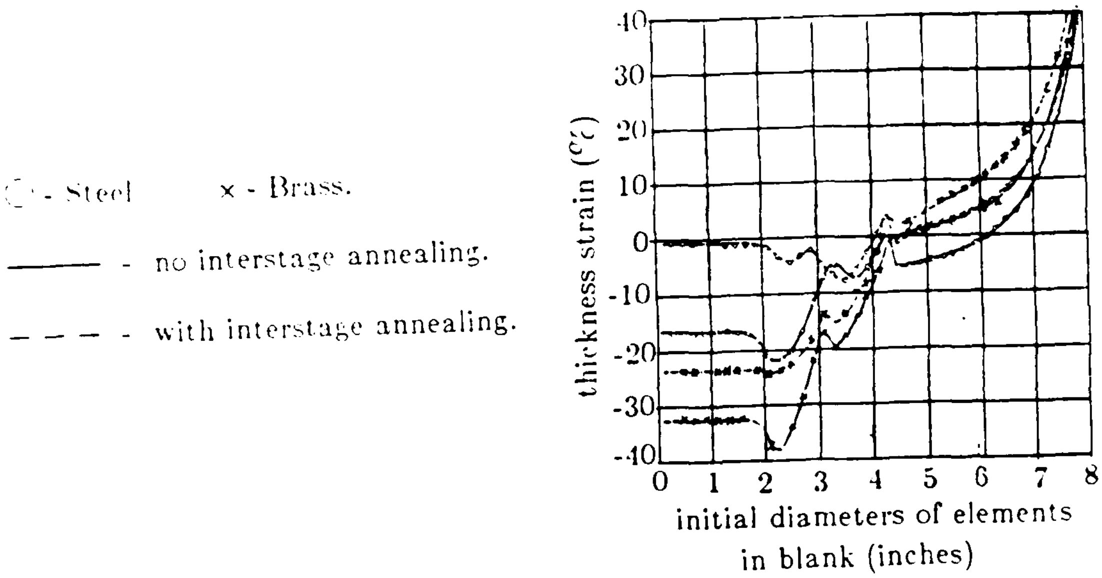


Figure 3-45. Effect of interstage heat-treatment on thickness strain distribution ([ChungSR], Fig. 15)

For a non-strain-hardening material, the tube-sinking mode that prevails after the initial embossing in redrawing has been accomplished, can be viewed as a steady state process. But, if the previous deformation and its strain-hardening are to be taken into account, a nonsteady process with the distribution of stresses, shown schematically in Fig. 24, will take place.

Examination of fractured cups ([ChungSR]) showed that tearing in redrawing did not occur at either of the necks of the previous drawing stage but in the punch-recess boundary, similar to that in drawing failure. The apparent reason for this is that the wrapping and stretching of a non-work-hardened bottom is wrapped and stretched around the punch radius gives way to the same failure mechanism of point D as in cupping (see Fig. 7). This corroborates the industrial practice of employing the largest possible drawing ratio in each preceding stage. Another conclusion (of a rather presumptive character) is that the Limit Redrawing Ratio (or as commonly represented: Limit Reduction Ratio, - LRR) of a sequence of redraws *decreases* by a

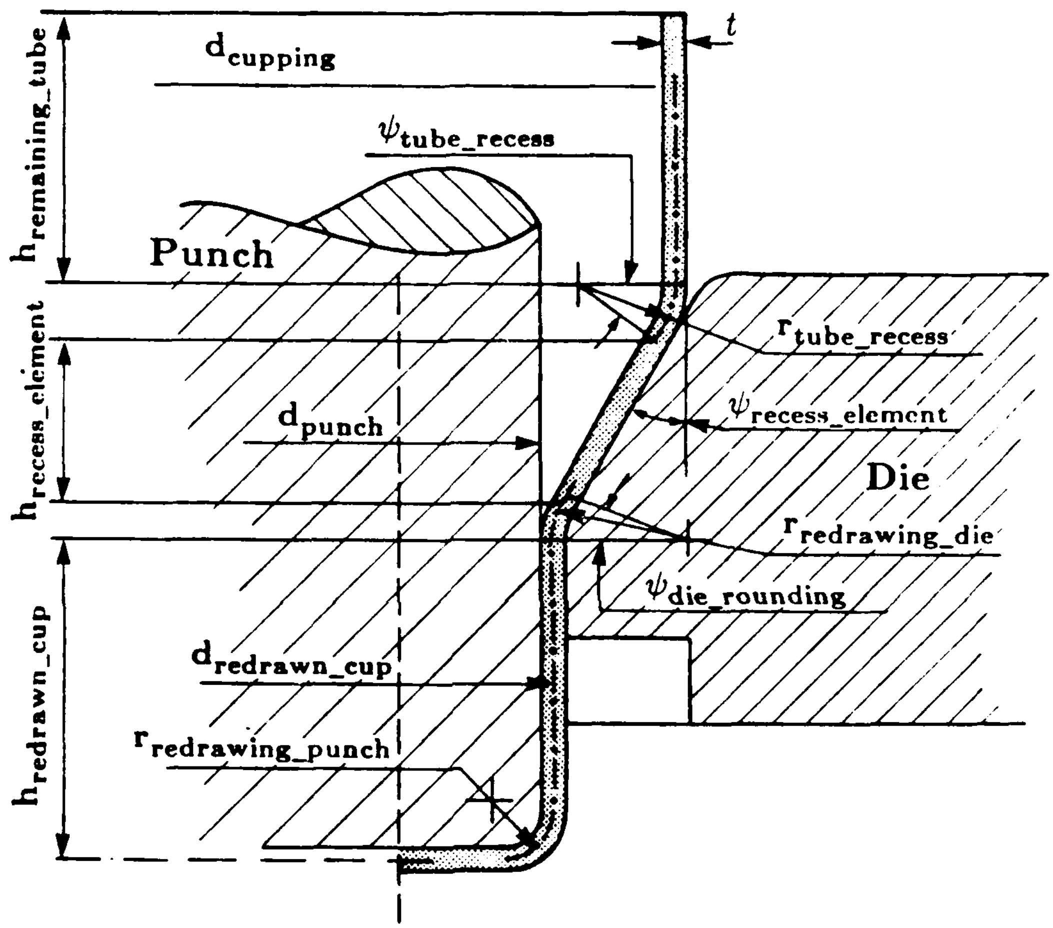


Figure 3-46. Redrawing through a conical die with no supporting sleeves: schematic apparatus

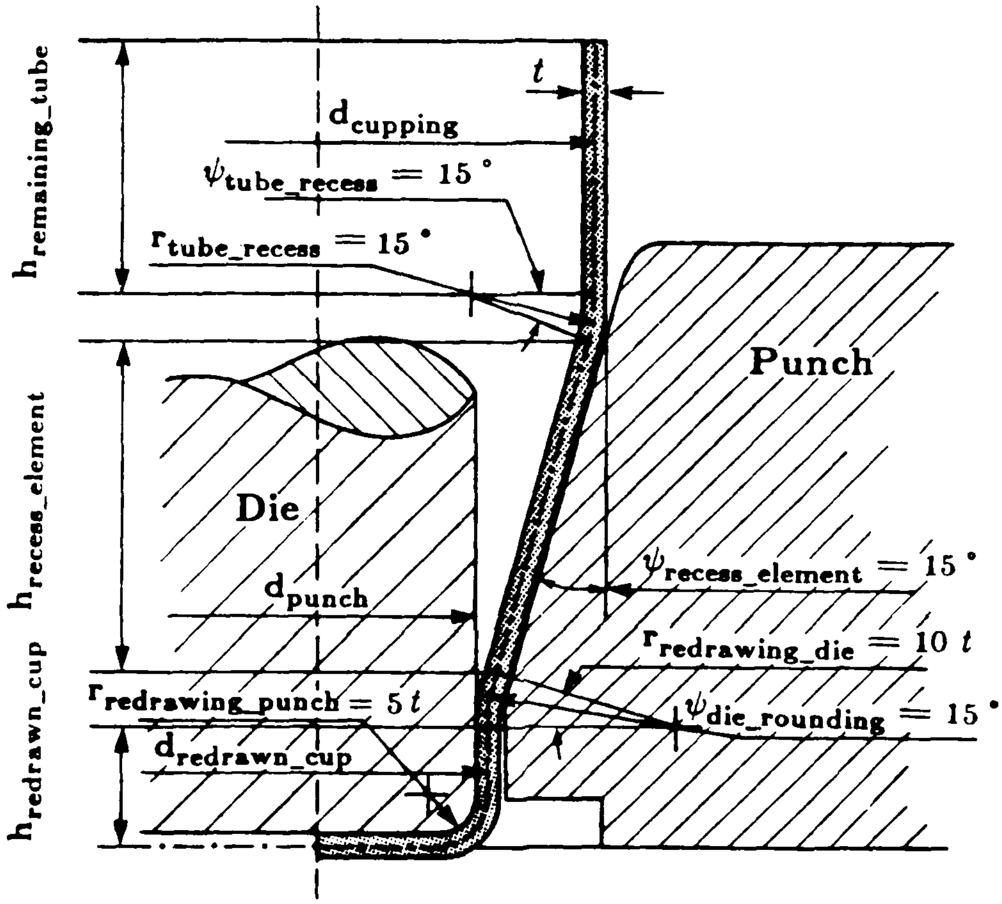
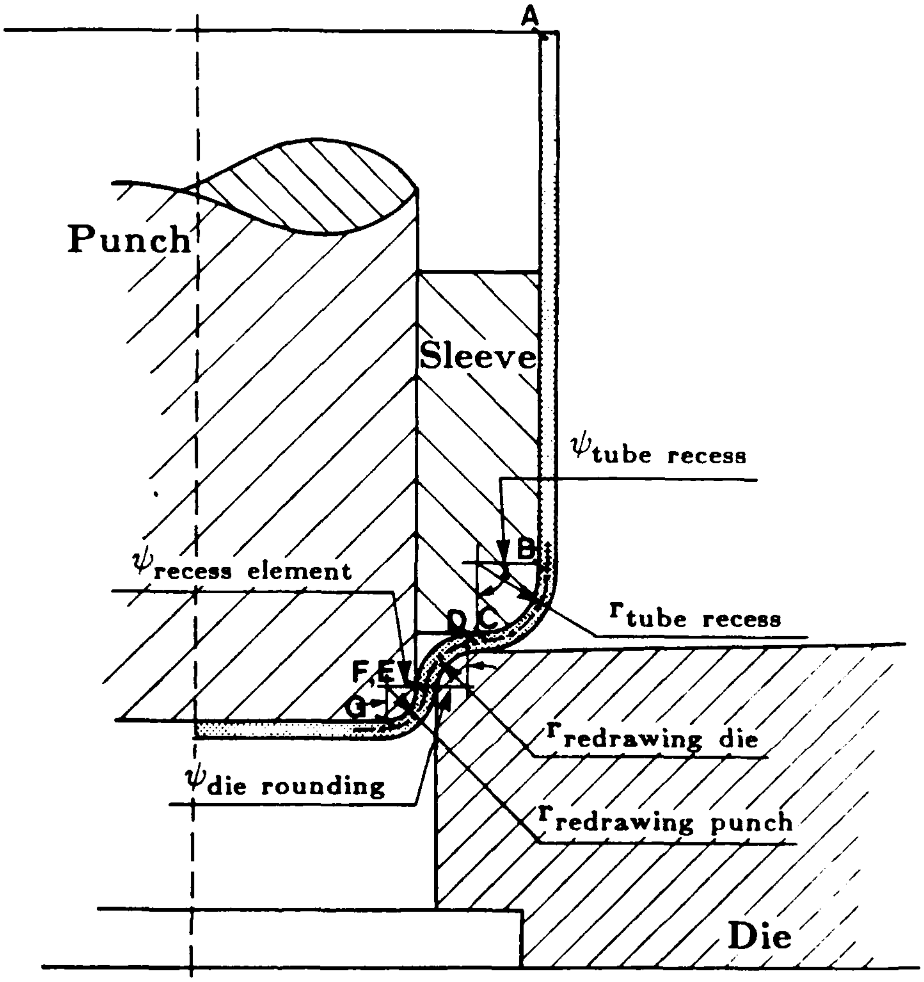


Figure 3-47. Redrawing through a conical die with no supporting sleeves: optimum conditions



optimal redrawing design for the embossing stage of method *b* redrawing stipulates:

$$\psi_{\text{tube recess}} = \psi_{\text{die rounding}} = \psi_{\text{recess element}} = \frac{\pi}{2} .$$

Figure 3-48. Redrawing a deep, vertical cup, method *b*, the *embossing* mode: drawing regimes and drawn elements.

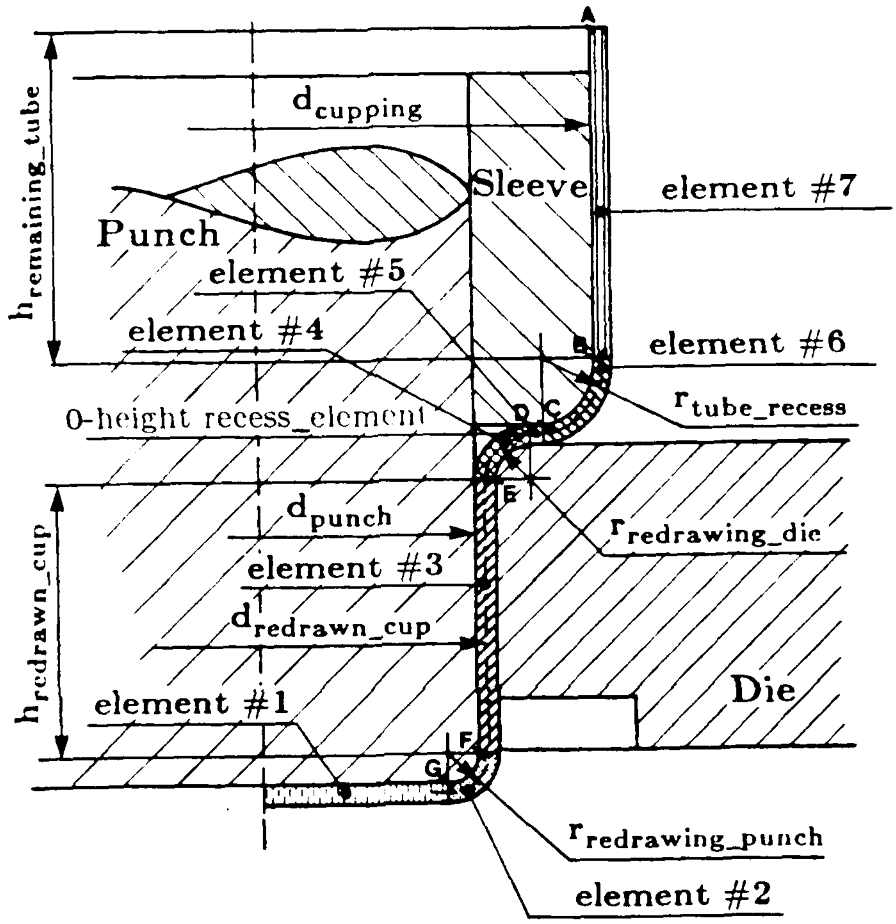


Figure 3-49. Redrawing, a deep, vertical cup, method *b*, *tube-sinking* mode: drawing regimes and drawn elements

constant rate. This statement is proposed upon observing empirical data that serve shops seeking redrawing limits. This practice certainly needs a more rigorous examination.

Hosford ([Hosfo81]) analyzed the effects of β and n on the Limiting Reduction Ratio (LRR) at the first redraw. He expresses it quantitatively in a formula that has to be numerically evaluated as

$$\textbf{Eq. 33.}\quad \eta\,\beta^{n+1} = \left(\frac{2.781}{n}\right)^{n} \int_{1}^{\mathrm{LRR}} \left[\tfrac{1}{2}\,ln\left(\frac{\mathrm{LRR}^3\,(\mathrm{D}_{cupping}{}^2 - 1)}{\mathrm{X}^2 + 1}\right)\right]^{n} \frac{d\mathrm{X}}{\mathrm{X}}.$$

This equation complies with the general finding that as n increases, LRR decreases and yields the drawing ratio for non-workhardening materials that was obtained following Equations (18), (19) and (20).

$$ln(\mathrm{LRR}) = \eta\,\beta \quad \Big|\; n = 0.$$

3.2.7 Feasibility Classification of Process Variables in Drawing Mode

The above discourse indicates that the boundaries of some process variables determine if feasibility of a draw can be satisfied. Parametrizing other process variables is more of a matter of fine design, and variables are usually obtainable within normal industrial usage. Complying with a general design approach of *Generate & Test*, the following section is concerned with classifying process variables and especially with formalizing the *Test* portion, in the *drawing* mode.

Feasibility is concerned with three types of occurrences:

- start of metal flow (incipient flow),
- defect-free completion and
- defect/failure development.

Criteria for the *start-of-flow* (for simple cupping or complicated redrawings) stipulate that each condition must be satisfied, whereas even one violation of flow conditions can bring about process failure or a defect. Hence, in deep-drawing processes, a *feasibility test*, in addition to producing a binary result of the type: { go; no-go } can indicate if the operation is *definitely not feasible* or if certain modifications may make it feasible. The following three states of deformation are thus distinguished:

Feasibility - in which metal flow is initiated and completed successfully.

Rectifiability - here the flow is initiated but cannot be completed without defects.

Infeasibility - refers to metal flow which cannot be initiated.

Feasibility is satisfied if certain operating parameters exceed certain *threshold* values. These variables will henceforth be referred to as *principal* process-variables. Other variables that may well be crucial to the success of the operation but are generally *attainable* in normal application, become a matter of finer design stages and be referred to as *secondary* variables. Principal process variables have, therefore, a significant role in determining the feasibility of flow-initiation and defect-free completion. For assessing feasibility, optimal (practically optimal) values of secondary process variables will be employed. The following classification modifies an account given by Hobbs and Duncan ([HobbsL4]).

- Principal feasibility process-variables:

  i. Press and Drawing Method
     - punch force (P),
     - blankholding force ($F_{blankhold}$).
     - type of drawing operation (e.g. cupping, direct, method-b, vertical redrawing)

  ii. Sheet/plate material:
     - stress-strain relationship (curve, n - strain hardening exponent),
     - limit-strains (realized in a Forming Limit Diagram): for the compression regime, - ϵ_θ (checked in the zone undergoing maximum accumulated squeezing), and thinning - ϵ_z (checked against TT),
     - normal anisotropy - R - planar to thickness strain ratio,
     - ΔR - planar anisotropy.

  iii. Geometry
     - depth-of-cup ratios - D, HR, RD, Tap,
     - wall-thickness ratios - TR, FTR,
     - die-rounding-radius ratios - DRR, DRT, - if determines workpiece shape,
     - punch-rounding-radius ratios - PRT, PRR, - if determines workpiece shape.

- feasibility-independent variables, i.e.: variables that have an effect on feasibility in borderline situations are:

  i. Lubricant:
     - Temperature sensitivity,
     - Stability,
     - Pressure sensitivity.

  ii. Tooling:
     - Type of shape/curve of die - (straight, tractrix, ...),
     - Stiffness/flexibility of blank-holding.
     - Die edge rounding, for not-flanged cups,
     - Surface roughness (affects friction),
     - clearance between die throat and punch stem.

  iii. Sheet/plate material:
     - Surface roughness (affects friction),
     - Strain rate sensitivity of the flow-stress,

  iv. Blank:
     - surface condition (affects friction),
     - Concentricity of draw.

  v. Press - mechanical features:
     - Ram speed,
     - Blank-holding method,
     - Frame Stiffness and accuracy.

The ultimate decision about feasibility status rests with the test rules. They are typified by the following characteristics:

- Independence of affecting variables: Knowledge of test results is given in such a form that, when a certain drawing parameter is being tested, the rest of the process parameters/conditions are kept optimal.

- Material properties pertain to the type of deformation regime (compression, tension, directionality) rather than to the outcoming displacement.

- Validity of tests is preserved even when material properties are changing, e.g. change in yield stress in hot-forming does not affect the rules governing the deep-drawing of domed cups.

A "natural" form in which test knowledge, and some parts of the knowledge of design of the sequence of redrawn cups is presented, is:

$$\{ \text{scope—of—applicability, Test—Rule—contents} \}$$

Test-Rule-contents is schematically formulated as:

$$\left\{ \begin{array}{l} \bullet \text{ process parameters} \\ \bullet \text{ significant } \text{cup}_{\text{initial}} \text{ specifications} \end{array} \right\} \rightarrow \left\{ \begin{array}{l} \text{significant } \text{cup}_{\text{resulting}} \\ \text{specifications} \end{array} \right\}$$

"cup" is a generalized cup and process parameters have to be within the scope of applicability.

In testing the feasibility of consecutive states of the cup, two main features are evaluated:

i *Shape* of the cup and the deformation zone,

ii *Mechanical properties* of the worked-on material and their change during the deformation.

Test Parameters

The testing of feasibility is done by verifying that the *individual test rules* (abbreviated to: *test rules*) are satisfied, where each test rule checks one *test parameter* (T-P) at a time. The set of all applicable individual test rules that have to be satisfied is called: the *Inclusive Test Rule.* Due to the nature and independence of the individual test rules the inclusive test rule is a conjunction of applicable individual test rules. The discussion above focused on the plasticity test parameters. Those parameters and others, pertaining to the drawing mode, are listed below.

i. Machine T-P:

a. Machine-Yield T-P:

- Ram force sufficiency (to satisfy start of flow),
- Machine size sufficiency.

b. Machine-Defect-Prevent T-P:

- Blankholder force sufficiency (to provide the hold-down force),

- Proper machine structure (e.g. action type, drive).

ii. Yield T-P:

- $\bar{\sigma}_{\text{most resisting region}}$

iii. Defect-Development T-P:

- D - Draw Ratio (upper limit),
- UE - a lower bound on the most severe strain a particle in the blank undergoes
- HR - Height Ratio (upper limit),
- RD - Redraw Ratio (upper limit),
- DRR - Die Radius Ratio (upper and lower boundaries),
- DRT - Die Radius Thickness Ratio (upper and lower boundaries),
- PRT - Punch Radius Thickness Ratio (upper and lower boundaries).
- TT - Wall-Thickness Thinning (upper limit),
- FTR - Flange Wall-Thickness Ratio (lower limit),
- TR - Thickness Ratio (upper and lower boundaries),
- Tap - Conicity Severity (a function of cone angle, length of cone and relative thickness of the tapered wall).
- Ear - height of ears.

3.3 Structure and Organization of Deep-Drawing Rules

3.3.1 Premises in Formalizing Deep-Drawing Rules

Considering that the state of the technological knowledge of deep-drawing is: not fully-procedural, incomplete and composed of analytical and empirical components that are not always compatible with each other, rule-based modeling is a rather natural means of formalizing it. Given the above features, when modeling the rules one has, to a great extent, to *synthesize* the rules rather than formalize existing knowledge. *Process capabilities* relate *deformation variables, material properties, operation parameters* and *workpiece specifications* to each other to produce a *feasibility* diagnosis. Deep-drawing rules are typified by the following characteristics:

- When deriving a set of empirical observations, the rest of the process parameters or conditions are assumed to be optimal.

- Material properties pertain to the type of deformation rather than to the type of displacement.

- Plasticity relations are valid even when material properties are changing during deformation (for instance, in hot-forming).

- Material properties and the flow characteristics are interrelated.

- Results of the analytic model constitute a basis for improvement. Fine adjustments of process-parameters will always be required, some obtained by physical trial & error in the workshop.

- The deep-drawing plan is a sequence of operations, each of which has to be specified by the *type of deep-drawing operation* and the *initial* and *resulting* workpiece specifications.

The rules are intended to permit the design of a feasible and *practically good* deep-drawing process consisting of one operation or a sequence of operations.

3.3.2 Shapes of deep-drawn cups

A cross section of a drawn cup is composed of a concatenation of *rotational elements*, i.e. *rings*. Each ring is composed of two sub-rings: the ring of the *main element* and the toroidal shaped ring of the *recess radius*. The starting point for the concatenation is arbitrary. Here we shall adopt a start at the external edge (flange) and a termination at the bottom. Thus, the last element - the bottom - has by definition a zero recess radius. The *wall* type of each ring is a predefined element taken from the *element dictionary* in Table 6. In Table 6 each element is defined by its code, associated parameters, and its *level*. The level implies producibility by a *main* deep-drawing operation (e.g. cupping, redrawing, tapering, hemisphering) or a *complementary* one (embossing, bulging, expanding, etc.). Usually secondary features are produced by complementary operations. The complementary processes are not dealt with here. Linkage to a next element is done through a toroidal segment of the previous element - the *fillet radius*. The fillet radius is *tangential* to both adjacent elements.

TABLE 3-6. Sample shape element types: codes, associated parameters and processes

Shape element dictionary				
Type	Name	Code	Parameter(s)	Process Level
_	horizontal	h	inside diameter	main
|	vertical	v	height	main
/	tapered	a1	+ (angle), height	main
\	tapered-reduced	a2	− (angle), height	complementary
	spherical	r1	+ radius, height	main
	spherical-reduced	r2	− radius, height	complementary
	emboss-out	e1	+ radius, height	complementary
	emboss-in	e2	− radius, height	complementary
	bulged-out	b1	+ radius, width	complementary
	bulged-in	b2	− radius, width	complementary
∪	∪-shaped	u1	+ radius	complementary
∩	∩-shaped	u2	− radius	main

3.3.3 Organization of deep-drawing rules

The knowledge of deep-drawing w.r.t. designing a sequence of operations can be put in the form of rules that are organized into three categories of usage:

1. *Design* the process outline of the deep-drawing operations,
2. *Test* the feasibility of an operation,
3. *Rectify* the process outline, i.e. the sequence of operations, if a defect or failure is predicted.

Some salient structural and semantic characteristics of the rules, of each category, are listed below.

Design Rules

The design rules (D Rules) are concerned with generating, backwards processing the product in the actual order of the sequence of deep-drawing operations which leads to a standardized raw-material. There are three categories of design rules:

1. find the previous *main* shape out of which the current one is likely to be drawn, and the process that can best do that.

2. design the elements of the *intermediate shape* of the cup that are not determined by the final shape, and

3. *match* the type of deep-drawing operation and the machine that are capable of performing the transformation of workpiece specifications.

Test Rules

Each individual test rule (T Rule) examines one *test parameter* (T-P) at a time. In some cases, several T-Ps are specified as the T-P of the test rule. In such case, a minute modification can be introduced to decompose the rule into a set of independent T Rules in terms of each of these T-Ps. T rules are valid within a predefined *scope* and are embedded within a *test-category*. As they are formalized they prescribe *necessary* but not *sufficient* conditions. Salient test parameters are determined by the principal feasibility factors (see § 2.7).

The scope of a test-rule is the 4-tuple:

$\{$ Process, Material, Cup—specifications$_{I}$, Cup—specifications$_{final}$ $\}$

There are three test-categories: $\{$ *machine, yield, defect-develop* $\}$.

1. *machine*, which includes the two subcategories:
   $\{$ *machine-yield, machine-defect-prevention* $\}$.
   machine-yield contains test-rules about the machine capabilities for inducing plastic flow; *machine-defect-prevention* contains rules about the machine capabilities for the prevention of defects.

2. *yield* pertains to the conditions for yielding.

3. *failure/defect develop* elaborates on the flow conditions under which a failure or a defect would occur.

The rationale behind distinguishing between *machine-category* and a general *category* is that the non-machine category contains rules that determine the feasibility of a process (of start-of-flow and defect-free completion) regardless of the *forces* imparted by the machine (press).

Rectify Rules

The *rectification* procedures, (R Rules) are specifically designed to modify the previous design but not to reactivate it. The *design* is reactivated if a *failure* is produced by the test procedures. A rectification procedure contains the following logic

1. Recognize if the detected failure/defect is *rectifiable.*

   A non-rectifiable process, in the context of deep-drawing processes, is one in which plastic or incipient flow in one moving part of the deformed cup is not reached.

   This part constitutes an interface between the test and the rectification modules.

2. Execute rectification of the sequence of operations.

   Rectification rules are grouped into categories by the type of problem they are designed to rectify. For example;

   i. *LD failure*: rectify by either employing less severe drawing conditions that would prevent necking, or improve the material properties (by heat treatment). Less severe drawing conditions can be obtained by introducing intermediate passes or by drawing through a curved (tractrix-shaped) die.

   ii. *Defect development*: rectify this by using either a special buckling-resisting mechanisms, or special lubrication methods, or select another material.

Computation Rules

To make the formalization more efficient, strictly computational rules (C Rules) are grouped into a fourth category. Parameters and variables that are computed in this category include: LD, blank sizes, punch force, blankholding force and wall-thinning.

Manipulation of Rules

It is assumed that a system that would search for rules will do it in compliance with an *ordering*[25] strategy, and the generation of automatic

solutions will be *depth-first* based. The rules in each category or subcategory are activated, one at a time, in the order of their anticipated viability. Hence, precedence of retrieval from the data-base determines the enactment of the rules. In the following section the actual operational ordering is maintained to the extent possible, in the absence of files and structural facilities within this text.

3.4 Deep-Drawing Rules

3.4.1 Variables

Given the specifications of the final required workpiece, namely its geometry and mechanical properties, the rules are set to design a process plan in terms of *design* variables. In order to transform the cup from one configuration to another, *operating-process variables* are computed and the validity of an operation is tested by *test variables.* The following variables, determined by the principal affecting factors, are embedded in the rules that comprise the above categories.

- *design*: the sequence of cups, in which each cup is specified by geometry, mechanical properties and the transforming processes. An axisymmetrical cup that may include vertical, tapered, hemispherical and planar elements (rings) and their recess radii, should be specified by:
  - ring type,
  - wall thickness of the ring (nominal, minimal, maximal, distribution),
  - size of the *main component* of each of the rings of the composite cup. The main component is a one-feature ring, of one of the types listed in Table 6.
  - recess radius of the element that is determined by either r_{die} or r_{punch}.

---

25. The *ordering* [illegible] that rules are evaluated upon the order in which they are put in the data-base.
The *depth-first* strategy is a graph searching strategy in which the search of the graph is done by exploring each possible path until either the required solution or a previously encountered node are encountered.

- The process is specified by the type of drawing process (vertical cupping, tapered cupping, method-*d* redrawing, stretch-forming, etc.).
  Primary *operating-process variables* are: Press sizes, P, $F_{blankhold}$.

- *Test variables*: D, HR, RD, RR, Tap, TR, FTR, DRR, DRT, PRT, (see nomenclature).

3.4.2 Scope of Application

The rules stated below have been developed for the following scope:

- *Machine*: hydraulic or mechanical presses of single, double or triple action. Bed and slide areas are assumed to be large enough to accommodate the die and to provide the space for the necessary accessories, or else can become feasibility variables.

- *Deep-Drawing Processes*:
  cupping, redrawing, tapering, stretching, stretch-forming, sizing. Redrawing can be carried out by one of the methods described in Fig. 42.

- *Parts*: axisymmetrical, of monotonic cross-section: diameters not decreasing with distance from the orifice.
  Constraints on cup sizes needed, to comply with press and raw material sizes, can be introduced too.
  Shape features: rings of the following cross-sections: horizontal; vertical; tapered; hemispherical (a set of features taken from Table 6).

- *Dies: can be designed and manufactured to draw any acceptable cup, by any of the participating operations.*

- *Workpiece materials* as commercially used - carbon steels, alloy steels, stainless steels and alloyed aluminum.

- Optimization, or rather practical optimization, in the design of the process plan and the operating parameters is achieved by heuristic methods. These are based upon engineering practice, whenever reaching the exact theoretical optimum is not of practical significance.

3.4.3 A Note about Completeness

The rules that are formulated in the following sections bring forth the idea of putting the technological knowledge in a rule form. Although the set of rules covers major parts of the design of a deep-drawing process plan, it is obviously still not complete and is, by nature and definition, expandable. Eventually, the very structure of rule based systems is designed to cope with a large, volatile, knowledge base that is frequently being expanded and updated. However, the rules laid down in this chapter are "proof-tested", in that they have been utilized in an automatic process planning system ("AGFPO", [EshelBC]).

3.4.4 Initial Design of a Sequence of Deep-Drawing Operations

Design Category 1: Design Previous Main Shape

D Rule 1

If a composite cup is required **then** it should be produced by a sequence of operations, where each operation produces one new deformation zone.

D Rule 2

If $\text{shape}_{\text{previous}}$ is to be designed **and** reverse redrawing is not employed **then** it should consist of a zone that is destined to be deformed ($\text{deformed--zone}_{\text{previous}}$) and a zone that is to remain unchanged ($\text{undeformed--zone}_{\text{previous}}$).

D Rule 3

If the diameters of the elements of the composite cup, **and** their distances from the bottom, starting from the orifice of the cup, are monotonically nonincreasing **then** the composite cup can be deformed by a combination of: {cupping, direct redrawing, tapering, stretch-forming, stretching, sizing}.

D Rule 4

If deformation–zone$_{current}$ is to be identified **then** it should include a combination of elements such that it is producible by *one* of the participating processes, e.g. straight-cupping, method-*d*-redrawing, tapered-cupping.

D Rule 5

If deformed–zone$_{previous}$ is to be designed **then** deformation–zone$_{current}$ should be one that is producible in one operation.

D Rule 6

If deformed–zone$_{previous}$ is to be designed **then** it should be a straight, vertical non-flanged cup, i.e one that consists of a wall, a recess radius and a bottom, or a blank only.

D Rule 7

If shape$_{current}$ is a cup of one, two or three elements, **then** shape$_{previous}$ is a circular blank.

D Rule 8

If an axisymmetrical cup is to be drawn **then** the initial form of the raw-material of the blank is a circular plate.

D Rule 9

If the cross section of a set of consecutive elements of a composite cup can be contained within a cone whose wall thickness is 5% (a tentative value) of the orifice diameter **then** these elements can be accomplished by one *sizing* operation, which deforms a cone whose outside surface is of the size of the inner containing cone.

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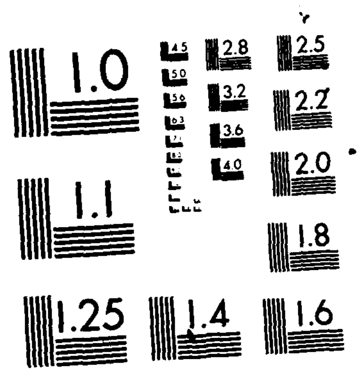

MICROCOPY RESOLUTION TEST CHART
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D Rule 10

If available processes can produce a set of elements of monotonically nondecreasing diameters **and** distances from the bottom, starting from the orifice of the cup **then** deformation–zone$_{current}$ is identified in the set of the bottommost elements of the cup.

D Rule 11

If the set of elements, starting from the bottom, is
{E4,E3,E2,E1} **or** {E3,E2,E1} **or** {E2,E1} **or** {E1} where:
E4 is an element of type: **v**,
E3 is an element of type: **h ; a1 ; r1**,
E2 is an element of type: **v ; a1 ; r1**,
E1 is an element of type: **h ; r1** and
E1$'$ is an element of type: **r1**
then the set can constitute one deformation–zone$_{current}$.

D Rule 12

If bend radii are to be specified and the element is one of the finished ones **then** they should comply with the recess radii of the cup$_F$.

D Rule 13

If a drawn element wraps itself around a convex curve of the punch head and the flange is restrained against sliding **then** the element undergoes *stretching.*

D Rule 14

If a drawn element wraps around a convex curve of the punch head **then** the element undergoes *stretch forming.*

D Rule 15

If *stretching* takes place in an element **then** that element undergoes thinning with the greatest thinning taking place at (approximately) one third the height from the bottom of the stretched element.

D Rule 16

If ideal *stretch forming* takes place **then** resultant thinning of the stretch-formed element is negligible.

D Rule 17

If the sizes of the geometrical features of the cup (e.g. DRR, DRT, PRR, PRT, Tap) are the required finished ones **and** final *sizing* is to be employed **then** it is necessary to design the intermediate shape so that each of the volumetric elements, within the zone to be sized, will undergo a minimal possible plastic deformation.

D Rule 18

If the sizes of the geometrical features of the cup (e.g. r_{recess} and $d_{orifice}$) are the required finished ones **and** final *sizing* is not employed **then** it is necessary to design the intermediate shape such that those features assume their final values.

D Rule 19

If the sizes of the geometrical features of the cup are not the required finished ones **then** it is necessary to design the intermediate shape with optimal bend radii.

D Rule 20

If a flanged deformation-zone is required **then** one should employ the first draw to obtain the outside diameter of the finished flange.

D Rule 21

If a blank diameter of the equivalent surface-area is computed **then** the actual blank diameter is larger by a certain constant.

D Rule 22

If the angle between adjacent elements in the cross section of the cup is less than π^{radians} (measured between the cross section of the main portion of the closer-to-orifice element and the main portion of the adjacent element) **then** the bend radius of the deformation-zone is determined by the punch.

D Rule 23

If the angle between adjacent elements in the cross section of the cup is greater than π^{radians} **then** the bend radius of the deformation-zone is determined by a die.

Design Category 2: Design the *Open Element* of $\text{Shape}_{\text{previous}}$

Definition: An *open element* is an element that is not *fully* determined by the required finished shape - cup_F.

D Rule 24

If the shape of the element is not fully determined by the cup_F **then** an open element needs to be designed.

D Rule 25

If an open element is to be designed **then** the main component of the element should not be narrower than the final element, and the bend radii need to be designed.

D Rule 26

If bend radii of open elements are to be specified **then** they should be designed such that their contribution to additional loads will be minimal.

D Rule 27

If bend radii are to be specified **and** the incipient load is satisfied **then** bend radii should be designed so that they bring minimal susceptibility to defects.

Design Category 3: Design of type of Deep-Drawing Operation

D Rule 28

If incipient flow of a redrawing pass cannot be satisfied **and** the type of deformation can be accomplished by a reverse redrawing process **then** reverse redrawing should be sought.

D Rule 29

If a redrawing pass is to be saved **and** the type of deformation can be accomplished by a reverse redrawing process **then** reverse redrawing may be employed.

D Rule 30

If the edge radius of the reverse redrawing die is greater than $10t$ and is also greater than 10mm (tentative design parameters) **then** reverse redrawing can be utilized.

D Rule 31

If no blankholder is needed **then** a one-stroke press is sufficient.

3.4.5 Testing the feasibility of an operation

Characteristics of the Tests

T Rule 32

If the operation has to satisfy a set of individual tests (regardless of their consistency) **then** these tests may be considered entirely independent.

T Rule 33

If a set of entirely independent individual tests have to be satisfied **then** the *inclusive test rule* is a conjunction of those individual tests.

T Rule 34

If a failure is predicted **then** the draw cannot be completed.

T Rule 35

If a defect is predicted **then** the draw can be completed but with an undesirable geometry (dimensions or surface finish).

T Rule 36

If the draw can be completed but undesirable geometrical perturbations are predicted **then** a defect is predicted.

T Rule 37

If a failure **or** a defect is predicted within the zone that is not to be machined away **then** the operation fails the test.

Test Category 1.1: Start-of-Metal Flow, Machine-Dependent

In the following rules **Scope** designates the conditions in which the rule is valid and **T-P** the examined test parameter.

T Rule 38

scope: any drawing process.

T-P: P.

If punch load cannot exceed P_{Max} **then** deformation cannot be accomplished.

T Rule 39

scope: any drawing process.

T-P: P.

If a sequence of deep-drawing processes is employed **and** a particular geometric feature is obtained through a series of consecutive draws **then** it is sufficient to check if P_{Max} of the first operation (draw or stretch) can be attained.

Test Category 1.2: Defect Development, Machine-Dependent:

T Rule 40

scope: drawing mode, flanged cups, no blankholding force.

T-P: TR.

If TR exceeds a certain LTR that depends upon the $\bar{\sigma}$–$\bar{\epsilon}$ curve, Young's Modulus and the buckling modulus **then** a cup which is safe from wrinkling can be drawn, without using a blankholder.

T Rule 41

scope: cupping, medium and thin blanks, flanged cups.

T-P: blankholding pressure: $p_{\text{blankholding}}$.

If blankholding force provides a minimum value of $p_{\text{blankhold}}$ **then** wrinkling of blank edges or puckering on the boundaries of the die recess can be avoided.

Test Category 2: Yield:

T Rule 42

scope: composite cups, redrawing or stretch-forming.

T-P: $\bar{\sigma}$.

If flow-resistance is to be tested **then** it is sufficient to test imparted incipient flow in the orifice of the deformation–zone$_{\text{current}}$.

T Rule 43

scope: composite cups, redrawing.

T-P: $\bar{\sigma}$.

If the flow stress in the most flow-resisting zone is adequate **then** *yield* conditions are satisfied.

Test Category 3: Defect/Failure Development

Failure

T Rule 44

scope: drawing mode.

T-P: D, HR.

If D and HR exceed LD and LHR, respectively, **then** a tear in the boundary of the cup at the {punch fillet - wall} (point "D" in Fig. 7) is predicted (i.e. operation cannot be completed).

T Rule 45

scope: drawing mode.

T-P: RD, RR, Redrawing HR.

If RD exceed LRD **then** a tear in the boundary of the {punch fillet - wall} (point "F" in Fig. 49) is predicted (i.e. operation cannot be completed).

note: the above rule can be also formulated in terms of RR.

T Rule 46

scope: stretching and stretch-forming modes.

T-P: TR.

If TR exceeds LTR **then** a tear in the hemispherical section, located approximately at one third of the height, would occur (i.e. stretching or stretch-forming cannot be completed).

T Rule 47

scope: drawing and stretch-forming modes, tapered and hemispherical deformation-zones.

T-P: D, HR.

If the deformed zones are tapered or hemispherical **then** $LD_{\text{tapered or hemispherical}}$ and $LRD_{\text{tapered or hemispherical}}$ that correspond to $LD_{\text{vertical cup}}$ and $LRD_{\text{vertical cup}}$, which govern the drawing limits can be formulated.

T Rule 48

scope: any drawing mode, exponential stress-strain relationship.

T-P: $UE_{compression}$ (lower bound, does not take into account the route of deformation).

If $ln(UE_{compression}) \leq |n|$ **then** no more deformations can be sustained by the workpiece.

Defects

T Rule 49

scope: any drawing.

T-P: DRR, DRT.

If DRR $<$ LDRR **and** DRT $<$ LDRT **then** galling may occur at the boundary of the cylindrical wall.

T Rule 50

scope: vertical cupping and multi-stage drawing.

T-P: PRR.

If PRR $\leq$ LPRR **then** severe thinning may occur at the orifice of the portion of the cup impressed by the punch recess radius.

T Rule 51

scope: one stage hemispherical drawing, hemispherical cups:

T-P: TT.

If TT $\leq$ LTT **then** hemispherical drawing may be completed.

T Rule 52

scope: tapering.

T-P: Severity of drawing tapered cups (Conicity Severity): Tap.

If $Tap_{drawn\ zone} \geq LTap$ **then** puckering may occur in the boundary between the conical wall and the die recess radius.

T Rule 53

scope: straight redrawn wall obtained through an intermediate tapered deformation-zone.

T-P: Tap.

If $Tap_{\text{drawn zone}} \geq LTap$ **then** puckering may occur in the bottom of the tapered zone.

T Rule 54

scope: cupping, flanged cups.

T-P: FTR & TR.

If $FTR \leq LFTR_{Max}$ and $TR \geq LTR_{Min}$ **then** the cup may be drawn without a blankholder.

T Rule 55

Scope: *drawing* mode, exponential $\bar{\sigma}$–$\bar{\epsilon}$ relationship.

T-P: Springback.

If $\sigma_U/Y > e^{\mu\alpha}$ (α is the bend angle) **then** springback will not constitute a defect ([Hosfo], 15-6).

3.4.6 Rectification processes

General Design

R Rule 56

If a Min{cost} process-plan is sought **then** it is a good design practice to minimize the combined number of operations (draws, passes and heat-treatments).

Rectification Category 1: Violated LD (or LRR) Rectification

R Rule 57

If the required D or RD is greater than $LD_{\text{instantaneous}}$ **or** $LRD_{\text{instantaneous}}$ **then** the introduction of intermediate passes such that each complies with a proper $LRD_{\text{instantaneous}}$ is necessary.

R Rule 58

If a hemispherical cup cannot be drawn in one stage **then** it may be drawn by a two-stage operation in which the first stage produces a vertical-walled cup.

R Rule 59

If a material responds to heat-treatment (annealing, tempering) **then** it should be introduced whenever ϵ_U **or** the Max. allowed number of redraws is reached.

R Rule 60

If interstage heat-treatment (annealing, tempering, etc.) is performed **then** strain history is nullified.

R Rule 61

If multistage drawing is introduced **and** the difference between $\text{wall}_{\text{current}}$ and $\text{wall}_{\text{next pass}}$ is no less than the sum of optimal die and punch profile radii **then** the intermediate pass should be designed such that the outcoming cup will be of optimal die and punch profile radii.

R Rule 62

If multistage drawing is introduced **and** the difference between $\text{wall}_{\text{current}}$ and $\text{wall}_{\text{next pass}}$ is less than the sum of optimal die and punch profile radii **then** the intermediate pass should be designed such that the outcoming cup will have a zero-length sloped recess element **and** optimal die and punch profile radii.

R Rule 63

If multistage drawing is introduced **then** in each intermediate pass, except for the last one, the outcoming cup will utilize the $\text{LRD}_{\text{instantaneous}}$.

R Rule 64

If multistage drawing is utilized **then** a practical approach is to consider the available $LRD_{instantaneous}$ as the one pertaining to the current pass, regardless of the extent to which previous draws utilized the available LRDs.

R Rule 65

If a combined first-stage draw and subsequent reverse redrawing is used **then** a triple-stage-action press is required (Industrial Practice).

Rectification Category 2: Defect Rectification

Note: only rectifications of wrinkling and puckering are elaborated on below.

R Rule 66

If wrinkling or buckling are anticipated **then** reduce the compressive stresses.

R Rule 67

If compressive stresses are to be reduced **then** introduce intermediate passes.

R Rule 68

If susceptibility to flange buckling is to be reduced **then** increase FTR.

R Rule 69

If FTR has to be increased **then** introduce intermediate redraws.

R Rule 70

If incipient puckering or undesirable nonuniform wall-thickness are evident **then** introduce complementary *ironing* to remove them.

R Rule 71

If a tapered or a horizontal element cannot be completed in one draw **then** by adding portions of the element in a series of redraws, build it up towards the bottom and the center (the axis of rotational symmetry).

R Rule 72

If a severe cone or a deep-concave cup cannot be drawn in one tapering operation **then** draw it from an intermediate *stepped cup.*

R Rule 73

If an intermediate *stepped cup* is to be drawn, as a means of producing a severe cone **then** design it such that each step is drawn to the smallest possible diameter (final cone not intersected), the optimal recess element angle (15° tapered), maximal depth and optimal recess radii, provided that the accumulated height does not exceed the required finished height.

R Rule 74

If a redrawing operation has to produce an intermediate tapered recess element **then** simultaneously increase the length of the tapered element and deepen the vertical portion of the cup.

R Rule 75

If PRT < LPRT **and** $r_{\text{punch corner}}$ that determines PRT is a feature of cup_F **then** first design an intermediate cup with $r_{\text{punch}_{\text{optimal}}}$ and redraw to cup_F with $r_{\text{punch corner}}$

3.4.7 Computation of Deep-Drawing Parameters and Plasticity Features

Notations

C Rule - Computation Rule

C-P - Computed Parameter

Preparatory Steps: Determine Plasticity Mode and define Computed Variables
Assumption: computations manipulate cups of *uniform nominal wall-thickness*. Wall-thickness changes are computed in the next stage.

C Rule 76

C-P: deformation mode.

If the height or length of the main element is zero **then** the *embossing* mode only is performed (the *drawing* mode has not yet started).

C Rule 77

C-P: HR_{taper}.

$HR_{taper} \equiv h_{tapered-cup}/d_{open-end}$.

C Rule 78

C-P: $HR_{hemispherical\ element}$.

scope: thin blanks, stretch-forming.

$HR_{hemispherical\ cup} = h_{dome}/d_{dome}$.

C Rule 79

C-P: $HR_{hemispherical\ element}$.

$LHR_{hemispherical\ cup} = \frac{1}{2}\ LD_{vertical\ cup}$.

C Rule 80

C-P: TR class for wrinkling prevention. ($TR = t_0 / d_{deformation-zone}$).

TABLE 3-7. Wrinkling-tendency classification by Thickness Ratio ([Eary], p. 145)

TR Class	
Name	Thickness Ratio
Very Thin	$TR < 0.005$
Thin	$0.005 \leq TR \leq 0.015$
Moderate	$0.015 \leq TR \leq 0.025$
Thick	$TR \geq 0.025$

C Rule 81

C-P: $RD_{tapered}$.

$LRD_{taper} \simeq LRD_{cup}$ / Tap (synthesized from [Jones] and [HobbsL4]).

C Rule 82

C-P: Conicity Severity Factor (Tap).

Tap = $LHR_{vertical\ cup}$ / $LHR_{tapered\ cup}$ (specific values to be synthesized from sample instances, e.g. those in [Jones]).

Optimal Sizes of Intermediate Redraws

r_{punch}:

C Rule 83

C-P: $r_{punch_{optimal}}$.

$\{4t \leq r_{punch_{optimal}} \leq 10t\}$.

The exact radius is not significant with regards to the LDR, but the smallest possible is recommended, to comply with other variables.

r_{die}:

C Rule 84

C-P: $r_{die_{optimal}}$.

$\{4t \leq r_{die_{optimal}} \leq 10t\}$.

The exact radius is not significant with regards to the development of a puckering defect, but the largest possible value is preferably used to minimize P.

Punch Force:

C Rule 85

C-P: P.

The overall punch load in the *drawing* mode is the sum of the individual loads: $F_{stretching}$, $F_{squeezing}$, $F_{bending}$, $F_{unbending}$ and $F_{tubesinking}$.

C Rule 86

C-P: P_{Max}.

An upper bound to force is

$$P_{max} = \frac{1}{4} \frac{\pi^2}{\sqrt{3}} d_{cup'} t_0 (\overline{\sigma}_0 + \overline{\sigma}) \, ln \left(\frac{D^2+1}{2} \right) \qquad \text{([DuncaJo])}.$$

$d_{cup'}$ - mid-wall diameter of cup.

C Rule 87

C-P: P_{Max}.

scope: one-stage drawing, high quality drawing materials:

$$\lceil P \rceil = K_1 \cdot \sigma_U \cdot L \cdot t$$

where: $\lceil P \rceil$ designates an upper bound estimate,

σ_U, the ultimate tensile strength,

L, the cup circumference at the smallest cross-sectional area and

t, the cup wall-thickness at the smallest cross-sectional area, and

$K_1 = 1.2\,(D - 1) \,/\, (LD - 1)$ ([Wick], [WilsoHG]).

C Rule 88

C-P: P_{Max}.

$$P_{max} = \frac{4\,\pi}{\sqrt{3}} \sigma_T \, r_{punch} \, t \qquad \text{([Backo], 11-15)}.$$

C Rule 89

C-P: P_{Max}.

scope: one-stage drawing, non-high quality drawing metals:

$$[P] = K_2 \cdot \sigma_U \cdot L \cdot t$$

K_2 is a coefficient that depends upon the depth of draw. For typical values for full cupping, see Table 8.

TABLE 3-8. Punch Load Coefficients (from [HobbsL4])

K_2-values for punch load		
D	HR	K_2-value
≥ 2.00	≥ 0.75	1.00
1.75	0.52	0.95
1.50	0.31	0.90
1.40	0.24	0.75
1.30	0.17	0.60
1.20	0.11	0.50
1.10	0.05	0.40

Wall Thickness Ratios:

C Rule 90

C-P: LTR for wrinkling-safe drawing *without* a blankholder.

$$TR \geq 1.725 \frac{\sigma_0}{E_{buckling}} \quad \Big| \; E_{buckling} = \frac{4\,E\,b}{\left(\sqrt{E} + \sqrt{b}\right)^2}.$$

C Rule 91

C-P: FTR & TR for drawing without a blankholder.

LFTR $\geq 1/3$ & LTR $\geq 1/20$. ([Lyman-4]).

Blankholding Force / Pressure:

C Rule 92

C-P: $p_{blankhold}$.

scope: cupping, annealed mild steels, thin walled blanks.

$p_{blankholding} \geq 400psi$.

C Rule 93

C-P: $p_{blankhold}$.

scope: cupping, medium and thin walled blanks.

$p_{blankhold} \geq 100psi$. ([Backo], §11).

C Rule 94

C-P: $p_{blankhold}$.

scope: cupping, medium and thin walled blanks.

$p_{blankhold} \geq 0.01\ Y$ ([ChungSA]).

C Rule 95

C-P: $p_{blankhold}$.

scope: cupping, annealed metals, medium and thin walled blanks.

$p_{blankhold} = \{\frac{1}{150} \text{ to } \frac{1}{200}\} \cdot [Y + \sigma_U]$ ([Lyman4]).

C Rule 96

C-P: $p_{blankhold}$.

scope: cupping, annealed metals, medium and thin walled blanks.

$p_{blankholding} \geq \{300 \text{ to } 500\}$ psi, for low carbon steel or:
$p_{blankholding} \geq \{1500 \text{ to } 2000\}$ psi, for Austenitic stainless steel ([HobbsL4]).

C Rule 97

C-P: $F_{blankhold}$.

scope: cupping, annealed metals, medium and thin walled blanks.

$F_{blankhold} \geq \frac{P}{3}$ ([Backo], §11, [Eary]).

C Rule 98

C-P: $F_{blankhold}$.

scope: shallow drawings, low-carbon steels, thin-walled blanks.

The blankholding force is a percentage of the punch-force and is a function of the wall-thickness of the blank, as given in Table 9.

TABLE 3-9. Blankholding force as a function of Punch Force and wall thickness, for low carbon steels ([Lyman4]) .

Blankholding force as a percentage of punch force (P)			
t (inches)	Blankholder force - %	*t* (inches)	Blankholder force - %
0.005	85	0.050	23
0.010	67	0.070	14
0.015	57	0.100	9
0.020	50	0.125	8.5
0.025	44	0.187	8.25
0.030	39	0.250	8.00

C Rule 99

C-P: $F_{blankhold}$.

scope: cupping, medium-thin-walled blanks and thinner.

Min-$F_{blankhold}$ is given as a function of P and cup geometry, in Table 10. Coefficient K is 2 for stainless steel and brass, otherwise K is 1.

TABLE 3-10. Blankholding Force as a function of Punch Force for certain Die, Punch, and Cup Sizes (from [HobbsL4]) .

Blankholding Force in terms of Punch Force (P)			
$\frac{t}{d_{cup}}$	$\left\{\begin{matrix}\text{Punch}\\ \text{profile}\end{matrix}\right\} = \frac{1}{10}$	$\frac{r_{die}}{d_{cup}} = \frac{1}{5}$	$\frac{d_{cup}}{d_{blank}} = \frac{1}{2}$
1/1000	$K \times 0.6 \times P$	$K \times 0.8 \times P$	-
1/500	$K \times 0.45 \times P$	$K \times 0.65 \times P$	$K \times 0.85 \times P$
1/200	$K \times 0.25 \times P$	$K \times 0.4 \times P$	$K \times 0.5 \times P$
1/100	$K \times 0.18 \times P$	$K \times 0.25 \times P$	$K \times 0.3 \times P$
1/50	$K \times 0.13 \times P$	$K \times 0.18 \times P$	$K \times 0.2 \times P$

LD, LDR and LHR:

C Rule 100

C-P: LD, LRD.

scope: any drawing process, non-optimal or non-standard conditions, no blankholding force exerted.

$LD = LD_{optimal} \cdot t\text{–}factor \cdot DR\text{–}factor \cdot PR\text{–}factor,$

$LRD = LRD_{optimal} \cdot t\text{–}factor \cdot DR\text{–}factor \cdot PR\text{–}factor.$

C Rule 101

C-P: LD, LHR.

scope: cupping, blankholding force is exerted, non-optimal or non-standard conditions.

$LD = LD_{optimal} \cdot t\text{–}factor \cdot DR\text{–}factor \cdot PR\text{–}factor \cdot BH\text{–}factor$

C Rule 102

C-P: Blankholding-factor, - BH-factor

scope: cupping, blankholding force is exerted.

$\text{BH-factor} = \exp(\ 1 - F_{flange\ friction}/F_{punch}\ )$

C Rule 103

C-P: $F_{\text{flange friction}}$

scope: cupping, blankholding force is exerted.

$F_{\text{flange friction}} = \mu\, F_{\text{blankhold}}$. (typical μ is 0.02).

C Rule 104

C-P: LD, LHR.

scope: one stage flat cupping, thin walled cups.

Practically-optimal LDs and LHRs for flat cupping are given in Table 11.

TABLE 3-11. Practically-optimal LDs and LHRs for flat cupping (synthesized from: [WilsoHG], [HobbsL4]) .

LD & LHR in Flat Cupping		
Material	LD	LHR
Drawing quality rimmed steel	2.15	0.90
Deep-Drawing quality aluminum	2.20	0.95
Deep-Drawing cold rolled steel	2.25	1.00
Hot rolled deep-Drawing steel	2.25	1.00
Austenitic stainless steel	2.20	0.95
Brass and copper	2.20	0.95
Aluminum, 1100 series	2.10	0.85
Refractory metals	1.33	0.19

C Rule 105

C-P: *t-factor.*

scope: cupping without a blankholder, medium thickness and thick deformation-zone.

LD's for a range of steels, relative to a blank 100 mm diameter and 1 mm thick, (TR = 0.01) are given in Fig. 40. This diagram can be easily converted to a set of piecewise linear functions from of which the *t-factor* can be extracted.

C Rule 106

C-P: *t-factor.*

scope: cupping and redrawing processes, medium thickness and thick deformation-zone.

LDs and LRDs for a range of steels, relative to a blank 100 mm diameter and 1 mm thick, (TR = 0.01) are given in Fig. 40, in the portion pertaining to: "cracks in bottom". This part of the diagram can be represented in a tabular form.

C Rule 107

C-P: *t-factor*

scope: any drawing, $\{2 < \mathrm{DRT} < 10\}$.

approximate *t-factor* values:

$t\text{-}factor = 1 \quad \mid \{\mathrm{TR} < 0.015\}$,

$t\text{-}factor = 1 + \mathrm{TR} \,/\, 0.35 \quad \mid \{0.015 \;\; \mathrm{TR} \;\; 0.25\}$,

$t\text{-}factor = 1.1 \quad \mid \{\mathrm{TR} > 0.025\}$,

(synthesized from [ChungSE]).

C Rule 108

C-P: *PR-factor*

scope: thin, medium and thick walled cups, any drawing:

$PR\text{-}factor = 1 - 0.02\ \mathrm{PRT} \quad \mid \{\ 1 < \mathrm{PRT} < 5\ \}$

$PR\text{-}factor = 1 \quad \mid \{\ \mathrm{PRT} \geq 5\ \}$

(synthesized from [Lyman4] and [HobbsL4]).

C Rule 109

C-P: *DR-factor*

scope: thin, medium and thick walled cups, any drawing:

$DR\text{-}factor = 1 - 0.01\ \mathrm{DRT} \quad \mid \{\ 2 < \mathrm{DRT} < 10\ \}$

$DR\text{-}factor = 1 \quad \mid \{\ \mathrm{DRT} \geq 10\ \}$

(a rough, tentative approximation. Synthesized from [Lyman4] and [HobbsL4]).

C Rule 110

C-P: LHR

scope: one stage tapering, thin, tapered cups. $t > \frac{1}{200}\, d_{open-end}$.

$LHR_{taper} = 1/4$.

C Rule 111

C-P: LHR

scope: one stage tapering, thin, tapered cups. $t > \frac{1}{20} d_{open-end}$.

PRR > 10.

$LHR_{taper} = 1/2$ ([Jones]).

C Rule 112

C-P: LHR (by directly computing H_{Max}).

scope: one pass/stage tapering, tapered deformation-zone.

$H_{max} = 0.54 d_p - 0.16 d_d + 0.58 r_p + 46.8t - 0.36$

d_p - punch diameter,

d_d - die diameter,

r_p - punch radius,

sizes in inches. ([HobbsL4]).

C Rule 113

C-P: LD, LRD

scope: any drawing operation, TR ≥ 0.025, tapered deformation-zones.

$LD_{cupping,\ TR-thick} = 1.25\ LD_{cupping,\ TR-thin}$,

$LRD_{redrawing,\ TR-thick} = 1.25\ LRD_{redrawing,\ TR-thin}$,

In the range of medium-thickness deformation-zones LD and LRD values are obtained by linear interpolation.

C Rule 114

C-P: LSR

scope: hemispherical cup, $r_{sphere} \geq 100\ t$.

$LSR = 1/2$

LRR, *LRD*:

C Rule 115

C-P: Limiting Reduction Ratio (LRR).

scope: thin blanks, multi-stage, straight, vertical, redrawing with no flanges.

Typical LRR values for the first 4 reductions, in *conventional* and *reverse* redrawings as shown in Table 12.

TABLE 3-12. Conservative LRRs in Multistage Drawing (from [HobbsL4])

Practical Max. Reductions in Diameter in Multistage Drawing (with regard to diameter of previous stage)				
Thickness range (mm)	1-st draw	2-nd draw	3-rd draw	4-th draw
Conventional Redraws				
Alloy Steel				
- to 1.5	0.4	0.2	0.18	0.16
1.5 to 3.0	0.4	0.15	0.14	0.13
3.0 to 4.5	0.4	0.12	0.11	0.10
4.5 to 6.0	0.4	0.10	0.09	0.08
Austenitic stainless-steel, Brass, Copper				
- to 1.5	0.44	0.24	0.22	0.20
1.5 to 3.0	0.44	0.18	0.16	0.13
3.0 to 4.5	0.44	0.15	0.14	0.13
4.5 to 6.0	0.44	0.12	0.11	0.09
Successive Reverse Redraws				
Alloy Steel				
- to 1.5	0.40	0.26	0.22	0.20
1.5 to 3.0	0.35	0.32	0.15	0.13

C Rule 116

C-P: Limit Redrawing Ratio (LRD).

scope: high quality drawing materials, thin-walled deformation-zones, multi-stage, straight, vertical, redrawing with no flanges.

Limiting redraw ratios for optimal redrawing conditions are given in Table 13.

TABLE 3-13. Limiting Redraw Ratios (optimal redrawing conditions) ([Lyman4])

Limit Redrawing Ratios (Conventional Redraws*)				
Thickness range (% of blank diameter)	1-st redraw	2-nd redraw	3-rd redraw	4-th redraw
0.15 to 0.3	1.28	1.25	1.22	1.19
0.3 to 0.6	1.30	1.27	1.24	1.20
0.6 to 1.0	1.33	1.28	1.25	1.21
1.0 to 1.5	1.35	1.30	1.27	1.24

* For redrawing passes #5 to #8 LRDs are interpolated from the above table. The LRD of each stage displays a fixed rate of decline of $\simeq 3\%$, provided that ϵ_U is not violated. Thus for a TR of 1.0 the corresponding LRD values are: $LRD_{\#5}=1.21$, $LRD_{\#6}=1.18$, $LRD_{\#7}=1.15$, $LRD_{\#8}=1.12$.

Die Radius

C Rule 117

C-P: DRR.

scope: one stage non-hemispherical drawing.

$LDRR_{Min} = 2.$ $LDR_{Max} = 10.$

Thickness Change

Wall Thinning

C Rule 118

C-P: TT.

scope: one stage hemispherical drawing, hemispherical cups.

$t = t_0\ \epsilon_t$

C Rule 119

C-P: TT.

scope: stretching mode.

wall thickening strain[26]: $ln(\mathrm{TT}) = \epsilon_t$, $\qquad \epsilon_t = -2\ ln\left(\dfrac{d_{dome}}{d_0}\right)$.

C Rule 120

C-P: *t*.

scope: one stage hemispherical drawing, hemispherical cups.

$\mathrm{TT} = (d_{blank}{}^2 + h_{hemisphere}{}^2) \ /\ d_{blank}{}^2 \ = \ 1 + (h_{hemisphere} \ /\ d_{blank})^2$

([Lyman4]).

Flange Thickening

C Rule 121

C-P: TT_{flange}.

scope: drawing mode, flanged cups.

$\mathrm{TT}_{flange_{Max}} = -\sqrt{\mathrm{D}}$ (empirical, [Lyman4]).

Ultimate Reduction

C Rule 122

C-P: UE

scope: drawing mode, no thinning assumed.

$$\mathrm{UE} = ln\ \frac{d_{blank-area_{deformation-zone}} - d_{orifice-of-cup}}{d_{blank-area_{deformation-zone}}}\ .$$

Punch Radius

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26. R.F. Young, J.E. Bird and J.L. Duncan "An Automated Hydraulic Bulge Tester", in *Applied Metalworking*, Vol. 2, p. 1-11, American Society for Metals, 1981.

C Rule 123

C-P: PRT.

scope: thin and thick walled cups, multi-stage, straight, vertical, full cupping.

$r_{punch} \leq 10 \cdot t$ **and**

$r_{punch} \geq 6 \cdot t_{mild-steel}$ **or** $r_{punch} \geq 4 \cdot t_{Austenitic-stainless-steel}$

(synthesized from: [HobbsL4], [Eary]).

Deformation Zone and Blank Size Computation

C Rule 124

C-P: sizes of blank or deformation-zone.

scope: drawing mode, plane-strain deformation, relatively small thinning.

surface area of deformed $\text{zone}_{previous}$ is equal, for all practical purposes, to that of the deformed $\text{zone}_{current}$

C Rule 125

C-P: d_{blank}.

scope: drawing mode, relatively small thinning.

The sum of the surface areas of the cup elements is equal, for all practical purposes, to the surface area of the blank.

C Rule 126

C-P: d_{blank}.

scope: any drawing mode.

The constant by which the diameter of a circle whose area is equal to the cup surface-area is to be multiplied to obtain the desirable blank diameter is 1.128. ([Wick], 4,(21)).

C Rule 127

C-P: d_{blank}.

scope: stretching mode, thinning is significant.

the sum of the volumes of the cup elements is equal to the volume of the blank.

3.5 Implications of Formalization into Rules

The feasibility of formalizing the capabilities of a set of deep-drawing processes to produce a family of composite, axisymmetric cups has been shown above. 127 rules that are readily computerizable are elaborated. The rules combine theoretical plasticity and empirical knowledge, the former having priority whenever it constitutes a sufficiently good approximation. A plan synthesis tactics that will utilize this formalization has to be based on its particular properties, namely: organization and structure of the rules. Salient ramifications to a process planning method are, thus:

1. In designing an intermediate cup (in backwards planning: the cup at the start of current operation) two sequential phases can be clearly distinguished:
   - Phase I: Check if a set of constraints are met,
   - Phase II: "Optimize" the design, in accordance with the goodness-of-design criteria.

2. In evaluating the goodness of design criteria, a hierarchy of measures, w.r.t. each design feature can be constructed. For example, in determining an intermediate punch-driven rounding one would have to first satisfy the PRT criterion and then the PRR one.

3. The design activities are carried out upon the pattern: generate an initial design that meets goodness-of-design criteria and test that design for feasibility. If the test diagnoses failure modify the initial design, in such a way that the causes of the violation are rectified.

One result of this practice is that it is possible to separate the goodness of the design and the diagnosis of its feasibility. A "good" design can be thus applied at any state, even before its feasibility is assessed, though it may later be rejected. Considering the search in plan synthesis, depth-first generations largely correspond to best-first ones. It is therefore derived that a plan synthesis tactic that will henceforth be named: "Generate & Test and Rectify" (G&TR) reflects the nature of the knowledge of deep-drawing. The G&TR tactic manipulates the technological rules of deep-drawing in a system that automatically generates feasible, realizable, sound and practically good deep-drawing process outlines. This system is elaborated in the following chapters.

4. METHODOLOGY

4.1 General Approach

A system that is designed to generate multi-technology process outlines should be based upon the nature of the technological knowledge (TK). By this token, the logical sequence of analysis, which is pursued in this research is to first evaluate the TK. With the TK implying some essential elements of a plan synthesis method and a natural and hence preferable form the knowledge is represented in, an method for the automatic generation of multi-technology process outlines can be designed.

The rule-based modeling of contemporary deep-drawing knowledge in Chap. 3 renders it readily amenable to automatic reasoning, and thereby to intelligent automatic process planning. Rule formulations are relatively easily modifiable and expandable. Hence, the formulation of deep-drawing knowledge into a a rule form is designed not only to realize a specific model but also to substantiate a concept. The structure of each of the rules complies with a basic feature of deep-drawing: "validity within *scope*". Other salient features of the rules are outlined below. The controlling process planning tactic is: *generate* and *test_and_rectify*. The central idea of this strategy is: *Generate* an initial solution and *test* it. If the test produces failure try first to *rectify* the solution, and regenerate it only if rectification is not possible. The type of rectification is largely dependent upon the technology. In de-machining a rectification may state: "build back more material" if the part could not be realized from the given raw workpiece. In forming processes a common rectification measure is to introduce intermediate operations that either improve initial mechanical properties or make the strain path less severe. Since a sequence of machining and deep-drawing operations is sought, the rules manipulate the overall *shape* of the part and later on the cup rather than

isolated elements.

The main components of the AGMPO system (**A**utomatic **G**eneration of **M**ulti-technology **P**rocess **O**utlines) are outlined in Fig. 1.
The structural modules follow from the backwards planning methodology:

- the ACDP subsystem (**A**utomatic **C**ircumscription to get a **D**eep-drawable **P**reform) produces the preform out of which the required part can be machined.
- the AGFPO subsystem (**A**utomatic **G**eneration of **F**orming **P**rocess **O**utlines) generates the process outline to deep-draw a cup.
- The data base contains general material properties and the specific capabilities of the plant resources: raw material in stock and available machines.
- The output of both the preform and process outline designs is converted into graphic pictures by special-purpose interpreters.
- The supervising mechanism of G&TR is utilized by both systems. It will be substantiated in the context of the AGFPO subsystem.
- A special module for the **A**utomatic **G**eneration of the Inclusive test **R**ule - AGTR - assumes the "test" function within the AGFPO module. It is discussed in a separate chapter in view of its reasoning features.
- The inference machine provides the means to search and match data items of the knowledge base. The theorem proving capabilities of Prolog serve this ends. Some mechanisms to circumvent the rigid search routine of Prolog are elaborated upon below.

Since an objective of the research is to come out with a rather generalized and expandable process planning methodology, structuredness is sought in each of the levels of the system: the form the rules are given, the organization of files and the plan synthesis mechanisms.

4.2 The 'Generate & Test and Rectify' Mechanism

The main idea of G&TR is: "Basically, the examined hypothesis is good. If the current plan is infeasible, a plan based on maintaining the *principal* features of the intermediate subgoals should be tried". Other solutions are developed on the basis of maintaining intermediate subgoals. *Test* in G&TR

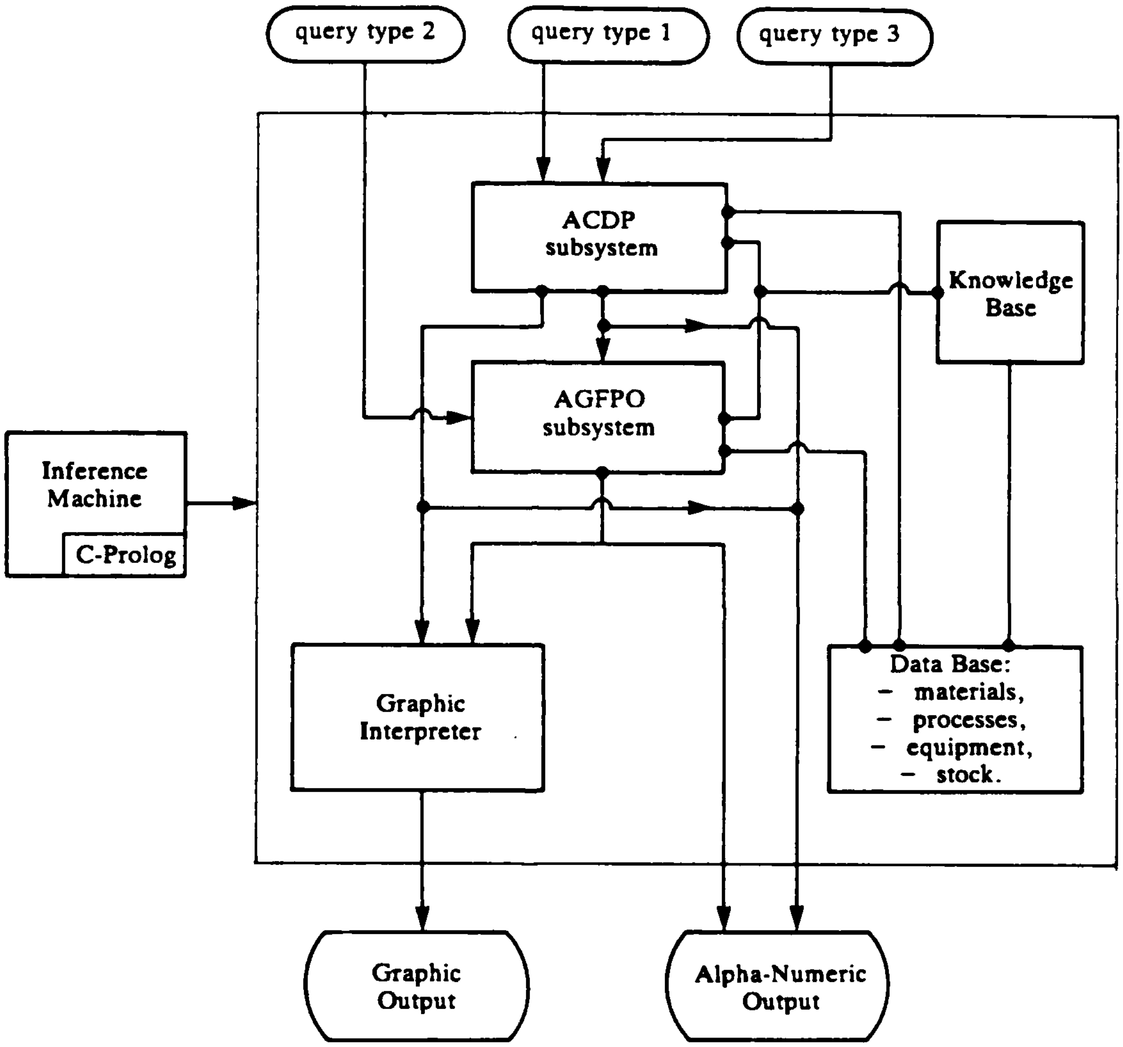


Figure 4-1. AGMPO System

detects the illegal elements of the plan and the *rectification* procedure modifies the first illegal element identified by the test procedure. Rectification is performed in stages, in each of them the initial and *primary properties of the final state* are preserved. As opposed to *G&T*, the test stage of G&TR stipulates a *three-way* possible outcome. The first two diagnoses: *succeed* and *fail*, correspond to those of *G&T*. The third, that distinguishes G&TR, is *rectify*. These diagnoses are summarized as follows:

- *Success*: all the operands of the plan/design are fully compatible with requirements. Hence the plan/design is accepted.
- *Failure*: a *principal* constraint/factor of the plan/design cannot be met.
- *Rectifiability*: a *minor* constraint/factor of the plan/design cannot be met, but some means of overcoming this type of failure are known.

G&TR proceeds in two phases. In the first stage a hypothesis is generated. This hypothesis must be tested. If the test succeeds the hypothesis becomes the solution, otherwise either a regeneration is invoked or the rectification procedures are called. The decision which path to follow is determined by the test stage. The rectified plan is put to test only if it is generated by a hypothesis-based procedure. This planning process continues recursively.

The following algorithm of G&TR gives it as an abstract (domain-independent) tree of procedures. This definition is applicable to the *plan* as well as to the *design* domain.

procedure $plan(S_I, S_G, P)$ (recursive):

input: initial and final states - S_I and S_G.
output: P - plan to transform initial state to final one.

if for the given set of conditions a plan is *generatable* **then**
{
generate Plan_i and *test* Plan_i, with outcome: Test_Result,
if Test_Result = "succeed" **then** { *report* "P=Plan_i" $\wedge$ *stop* }
else
{
Test_Result gives Violation and rectification status,
if Rectification status = *rectifiable* **then**
rectify Plan_i $\wedge$ *test_if_needed* $\text{Plan}_{\text{rectified}}$,
else *plan*(S_I, S_G, P), starting with next hypothesis.
}
}
else { *report* "fail" $\wedge$ *stop* }.

Procedure *plan* is the top G&TR routine. It proceeds in two phases. In the first phase a new plan is generated, if such plan is generatable, and tested. The test is especially suited to the specific plan and set of conditions. The test result may be *succeed*, *fail* as in conventional *G&T*, or *rectify*. *rectify* is issued when the *test* finds that the plan has a chance. *rectify* invokes a redesign of the unsatisfactory portion of the plan followed by a test, if needed. Any rectified subplan maintains the initial and principal final features of the infeasible portion, and can be thus readily embedded into the plan.

G&TR controls the generation of process outlines in the AGFPO subsystem and of the circumscribing preform in the ACDP subsystem. Its use in AGFPO is justified because it emanates from the characteristics of the KB, while in ACDP it emulates a convenient design practice. The deep-drawing KB implies that while the initial design is done backwards (de-forming), rectification is done forwards. This is derived from the main rectification rules. They usually reduce the severity of draws. When a forward type of design is used, sizes of the cups will utilize the maximum allowable strain and thus save subsequent tests. A common way of realizing rectification is by introducing intermediate

operations that either improve initial mechanical properties or make the strain path less severe. Rectification rules are grouped into categories by the type of violation they are designed to rectify. **R Rule 57**, for example, states:

If required Redraw-Ratio is greater than Limit—Redraw—Ratio$_{\text{instantaneous}}$ **then** the introduction of intermediate passes such that each complies with the appropriate Limit—Redraw—Ratio$_{\text{instantaneous}}$ is necessary.

The rectification procedure that is formulated upon this rule specifies a sequence of cups that will maintain the maximum allowed strain. Once the associated computational rules are fired the maximum diameter of each of the intermediate cups is determined.

The G&TR tactics is suitable for plan synthesis domains where the initial plan has a high probability of success or the rectifications are of relatively minor degree. Therefore it may be useful to limit the depth of rectifications pertaining to a particular hypothesis, otherwise the outcoming plan may become cumbersome and wasteful.

4.3 The 'ACDP' Subsystem

The ACDP accepts a CAD representation of the required part and turns out a CAM representation of a cup. The CAD representation of that cup circumscribes the CAD representation of the part. At this stage only axisymmetrical parts and cups are sought, therefore a 2D circumscription of the cross-sections of the cup and part is sufficient. The required part is a bi-monotonic polygon w.r.t. X and Y axes. It is represented by its cross-sectional contour as a concatenation of segments, starting from the outer bottommost one. The circumscribing preform of the deep-drawable type is a monotonic, of uniform-wall-thickness. Its CAM reprepresentation is a concatenation of "rings", each being composed of a main element (vertical, horizontal, tapered, etc.) and a recess radius. The recess radius is tangential to the main elements of the current and adjacent rings. The recess radii have to satisfy some minimum and maximum conditions, depending upon material type, mechanical properties and grain structure. The particular values of the recess radii within the boundaries are determined by the goodness-of-circumscription criterion.

The circumscription is performed in two stages. The first stage is irrevocable. It yields a piecewise linear medial and the minimum uniform wall-thickness within which the polygon can be circumscribed. The medial and the wall-thickness are extracted from the *uniform wall thickness circumscribing polygon* that is built w.r.t. either the internal or the external wall of the part. The second stage manipulates the medial. It attempts to smooth the medial in compliance with the minimum wall thickness and the recess radii constraints. This smoothing involves modifications of the initial medial and a trial-and-error type of setting the values of the recess radii within the constraints. Since several heuristic procedures for the smoothing are attempted, and none of them is guaranteed to succeed, this part is implemented as a RBS.

dddp (*d*esign a *d*eep-*d*rawn *p*reform) is the root procedure ACDP is built upon:

procedure: *dddp*(Part, Cup_F) (recursive):

input: Part - bi-monotonic polygon.
output: Cup_F - The final circumscribing cup.

□

if *generatable*(Part, Cup_H) **then**
{
generate(Part, Cup_H),
test(Cup_H, Part, Diagnosis),
if Diagnosis = "succeed" **then** {*report*("$\text{Cup}_\text{F} = \text{Cup}_H$") $\wedge$ *stop* }
else
{
if Diagnosis = "rectifiable" **then**
rectify_and_test_if_needed(Cup_H, Cup_F)
else *dddp*(Part, Cup_F) $\mid \text{KB}_{\text{next hypothesis}}$
}
}
else { *report*("fail") $\wedge$ *stop* }.

□

To avoid an undesirable explosion of the search space, rectification is applied only to the initial medial. Thus, if rectification fails, the supervisory

G&TR mechanism brings the search back to the initial medial and fires the next set of rectification rules on its basis. A structured view of the ACDP system is shown in Fig. 2.

4.4 The 'AGFPO' Subsystem

The basis for generating automatic process plans is already established in Chap. 3 where the TK of deep-drawing is extracted and put in the form of rules. The analysis of the TK implies that it is amenable to manipulation by a G&TR plan synthesis tactic. The specific G&TR application follows from the three categories the rules are grouped into, that correspond to G&TR stages. These categories include the following rules:

- generate the hypothesis, - plan the initial sequence of deep-drawing operations, - D Rules,
- test workability and realizability of the deep-drawing process outline, - T Rules, and
- rectify the process if a *formability* violation is predicted, R Rules.

A fourth category, in which computation rules of the first three categories are grouped, is introduced in Chap. 3 to make the formulation and search more efficient. It does not, however, make a new conceptual category. Each element in these categories is put in the form of a one-result rule and thus the rule based formulation of G&TR can readily be realized. The schematic structure of the AGFPO subsystem is shown in Fig. 3.

The scope of the technological knowledge already formalized in AGFPO is:

Machine: hydraulic or mechanical presses of single, double or triple action. Bed and slide areas are assumed to be large enough to accommodate the die and to provide the space for the necessary accessories, or else can become feasibility variables.

Deep-Drawing Processes: cupping, redrawing (methods a - d), tapering, stretching, stretch-forming, sizing.

Parts: axisymmetrical cups of monotonic cross-section. Monotonicity implies that diameters are not increasing as distance from the bottom decreases. Cup sizes have to comply with press and raw material sizes.

Shape features: rings of the following cross-sections: horizontal, vertical, tapered or hemispherical.

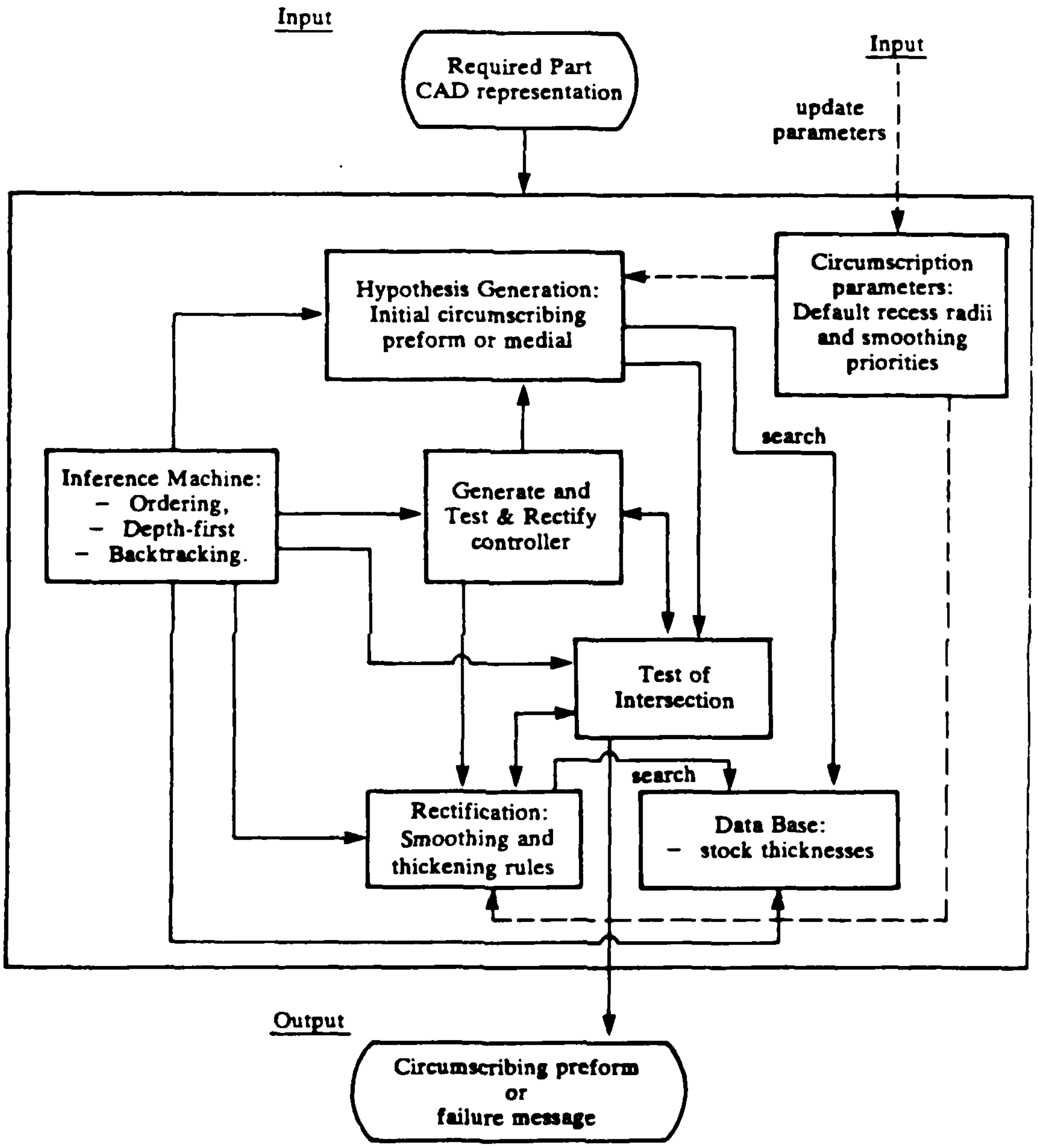


Figure 4-2. ACDP Subsystem

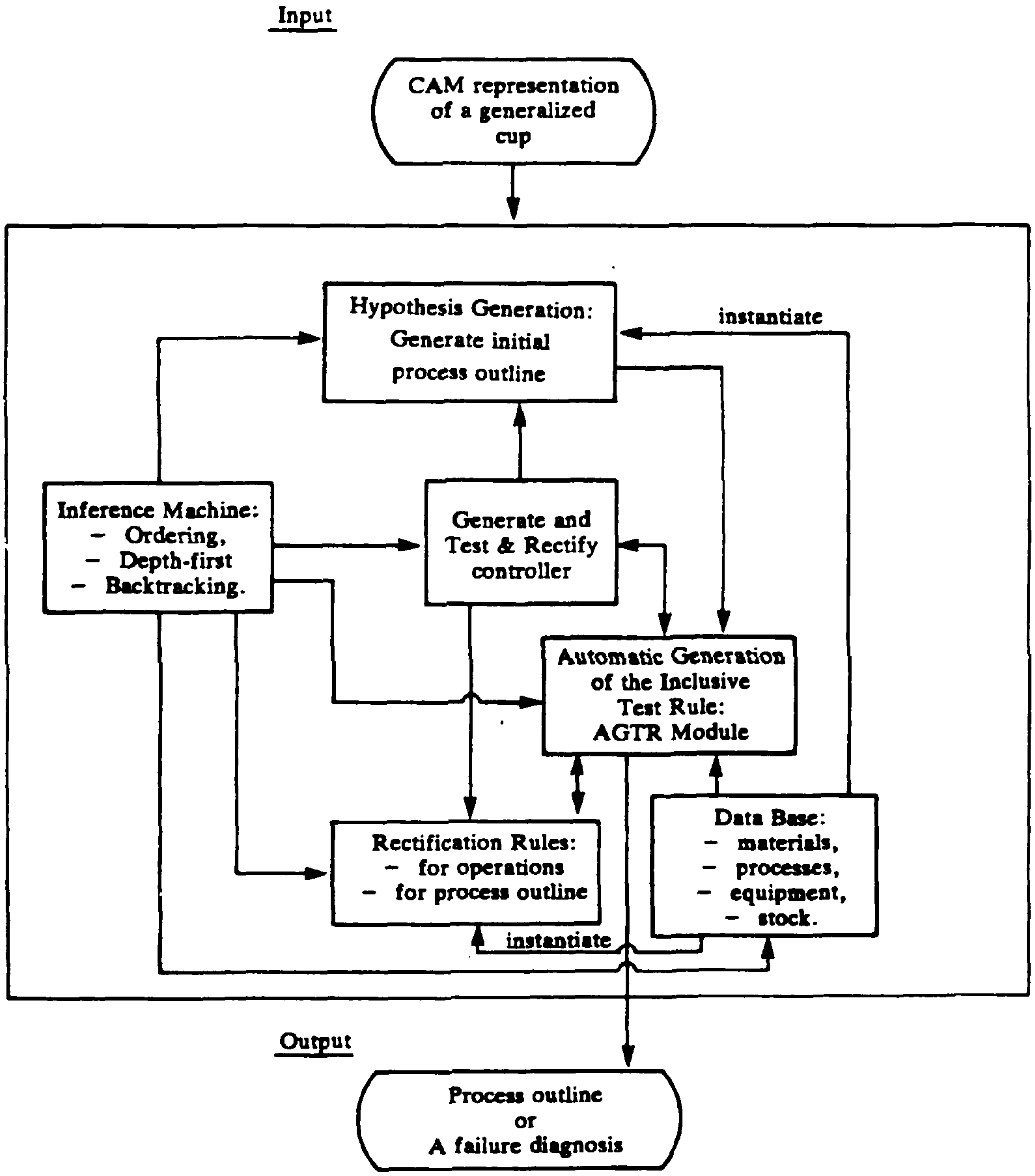


Figure 4-3. AGFPO Subsystem

Dies: can be designed and manufactured to draw any acceptable cup, by any of the participating operations.

Workpiece materials as commercially used - carbon steels, alloy steels, stainless steels and alloyed aluminum.

Optimization: practical optimization, in the design of the process plan and the operating parameters, is achieved through heuristic methods based upon engineering practice, whenever the exact theoretical optimum is not a practical necessity.

The search for matching rules in the KB is controlled by *ordering* strategy and automatic solutions are built following *depth-first* strategy. Rules in each category or subcategory are activated, one at a time, in the order of their anticipated effectiveness.

Given the specifications of the final required workpiece, namely its geometry and mechanical properties, the rules are set to design a process plan in terms of *design* variables. In order to transform the cup from one configuration to another, *operating* process variables are computed and the validity of an operation is tested by *test* variables.

- *Design* variables; An axisymmetrical cup that may be built of vertical, tapered, hemispherical and planar elements should be specified by:
  - ring type,
  - wall thickness of the ring (nominal, minimal, maximal, distribution),
  - size of the *main component* of each of the rings of the composite cup. The main component is a one-feature ring, of one of the types listed in Table 6.
  - recess radius of the element, assuming that two adjacent elements are tangential to a connecting recess arc. The recess radius may be determined by either $\text{rounding}_{\text{die}}$ or $\text{rounding}_{\text{punch}}$.

- *Process* variables: The process is identified by the type of drawing process, e.g. vertical cupping, tapered cupping, "method-*d*"-redrawing, stretch-forming. *Primary* operating process variables include: press structure, press sizes, punch force, blankholding force. Press speed, lubrication sensitivity and stress - strain-rate relationship are typical *secondary* operating variables w.r.t. feasibility.

- *Test* variables predict the mode of metal flow. They mostly test for lower bound, but some have a range, i.e an upper bound too. Some representative deep-drawing test variables include:
  - Draw Ratio (upper limit),
  - Redraw Ratio (upper limit),
  - Die Radius Ratio (upper and lower boundaries),
  - Die Radius Thickness Ratio (upper and lower boundaries),
  - Conicity Severity (function of angle and length_{cone} / $\text{diameter}_{open\ end}$).
  - Difference in height of "ears".

The structure of the rules complies with a basic property of deep-drawing: "validity within *scope*". This property sets up the ground for constructing the appropriate set of tests to check feasibility of each operation.

The search for matching rules in the KB is resolved in the *order* rules are organized in the KB, and automatic solutions are built following the *depth-first* strategy. Test subcategories and rules within each subcategory are organized according to the significance of the test variable and the level of confidence of the particular test. Rules in the *design* and *rectify* categories are activated, one at a time, in the order of their anticipated success or preferable application too.

4.5 The Automatic Generation of the Inclusive Test Rule

An automatic plan synthesis system based on a G&T mechanism requires that the "test" component be automatic too. A test in such system typically assesses feasibility of an hypothesis rather than its goodness. The test problem thus involves two principal tasks:

- construct the appropriate test,
- carry out the test.

The type of the test, i.e. its outcome, does not interfere with its automatic generation.

The issue of constructing the *test* within a G&T system comes up when a fixed, predefined, test that will test any generation is not applicable. In this case the test has to be "tailored" for each set of conditions. A special case of tailoring occurs when the test the hypothesis has to meet is a combination of

individual tests. This form is named here the "inclusive test", - it includes several individual tests. Furthermore, in the context of deep-drawing the inclusive test is identified as a *conjunction* of individual test rules. This means that there is no "choice" as to which individual test is to be included in the inclusive test. The system for the *Automatic Generation* of the *inclusive Test-Rule* - AGTR - that suits the technological knowledge of forming processes, deep-drawing included, is described below.

The testing of the entire process plan, when forming processes are evaluated, requires a *forward reasoning* system because of the changing properties of the material being worked. When testing each operation one takes into account the deformation encountered in previous operations (strain history) and the route of metal flow in current operation, and not just the initial and final geometries of the workpiece.

The AGTR system is built as a two-layered, deterministic RBS. The upper layer - *abstract AGTR* - is the domain independent formulation, and the bottom layer contains the instantiated knowledge. The abstract AGTR subsystem guides a user in setting up the category test files and encoding into each file the appropriate TR's in a predefined structured form. The rules, in the abstract and the application layers, are put in Horn clause form.

The abstract AGTR mechanism is based upon the *activation* of rules. The inclusive test is a conjunction of individual active T Rules. A rule is active if its scope includes the problem, i.e. the initial and final specification of the part, the process and the material. The building of the inclusive test rule and actual testing proceed simultaneously. System aspects of the AGTR module include organizing the test KB in *test categories* and exchanging the next candidate test category with the one in the working memory. The simultaneous build-up and testing of the inclusive test is halted if one of the individual tests is not satisfied. The message is then passed on to the G&TR supervisor which decides if rectification or regeneration is to be executed.

The abstract test rule to determine the effect of a particular T Rule - TR_{ij} - exemplifies the abstract rule based formulation. "i" in this formulation designates the serial number of the T Rule and "j" its test-category.

Test—Rule$_{i,j}$ yields "$\neg$*fail* Mapping" **if**
Test—Rule$_{i,j}$ $\neg$*active* w.r.t. Mapping $\vee$
Mapping satisfies Test—Rule$_{i,j}$.

The above reads: "a test is considered to produce 'success' if either the rule is not applicable or else the test produces 'operation successful'"

The AGTR is implemented as a structured RBS. Conflict resolution is done by *ordering*; rules and facts are examined for match *sequentially*, within the working memory, and *backtracking* is used to search the state-space graph. Structuredness is implemented by storing the individual test rules and the relevant facts of each category in separate category files that are read into the memory only when required. Validity of every T Rule is defined within a certain scope. Thus each category test-file is composed of the pairs: { scope-of T Rule, content-of T Rule }. Both predicates, 'scope-of T Rule' and 'content-of T Rule' have a category-dependent structure.

4.6 Hierarchical Structure in AGMPO

Hierarchy in the context the AGMPO system has two meanings. First it denotes a division between *conceptual* or *abstract*, and *instantiated* rules. The abstract rules do not pertain to specific entities while the instantiated ones do. The other kind of hierarchy may occur within each *layer*, either abstract or instantiated. It is the conventional, tree-like, hierarchy. These meanings are illustrated in the following example which shows some twigs branching out from the feasibility tree. The *root* rule defines the conditions for the feasibility of a process outline and the branches (rules) develop each of its RHS predicates. The rules are described as Horn clauses, with "," denoting "and".

Example: Conceptual and Instantiated Feasibility Rules

Conceptual Rules:

1: PO_k is feasible **if**

1 First operation is feasible,
2 Each of the operations is feasible,
3 The sequence is feasible,
4 Cost constraint is satisfied.

1.1: The first–operation$_j$ is feasible **if**

1 The raw_material entering the process is appropriate,
2 Changes of workpiece specifications conform to the type that can be handled by the process,
3 Initiation of flow can occur,
4 The process can be completed without defects,
5 Appropriate and sufficient equipment exists (main machine and auxiliary equipment).

1.1.1: The raw_material–item$_l$ of the first operation is appropriate **if**

1 It is of the required material,
2 It is of the right form (sheet; tube; rod; etc.), - and the fiber direction is appropriate,
3 It is in the right mechanical condition,
4 Each raw_material unit in stock can supply at least one workpiece,
5 There are enough units in stock to provide the required quantity.

Instantiated Rules:

1.1.1.4: a unit of raw_material–item$_l$ in stock is sufficient **if**

- the raw_material type is sheet,
- the thickness of the raw_material unit = the thickness of the blank,
- the diameter of the raw_material unit $\geq$ the diameter of the required blank.

1.1.1.4: a unit of raw_material–item$_l$ in stock is sufficient **if**

- raw_material type is plate,
- the thickness of the raw_material unit = the thickness of the blank,
- the diameter of the raw_material unit $\geq$ the diameter of the required blank.

4.7 Search and the Inference Machine

AGMPO utilizes the theorem proving and search facilities of Prolog. The theorem proving features suffice for both the ACDP and the AGFPO modules. The built-in depth-first & backtracking search works quite satisfactorily for the AGFPO subsystem but not for ACDP. The reason stems from the nature of the technological knowledge. While the 'design' and 'rectify' portion of the deep-drawing knowledge can be put in a definite order the rectification rules for smoothing cannot. For example, it goes without saying that if a series of draws can achieve a deformation, annealing would not be employed. In contrast, in smoothing the medial, there is no fixed order in which the rules can be put in. In addition, the preferable preform can be determined only after its process outline is evaluated. Before that is done it is hard to tell what combination of wall-thickness and recess radii is the best.

To overcome the shortcomings of the depth-first search and ordering conflict resolution, an extensive use of "!"s ("cuts") and the "cut-fail" combination is introduced. With the help of these mechanisms ACDP allows only one level of rectification to take place for every ready-for-smoothing medial, which serves as an hypothesis. The "cut" prevents backtracking from trying to resatisfy predicates that precede it and the "fail" when reached, enforces unconditional failure. When a "cut-fail" checkpoint is reached, an irrevocable failure of the term within which it appears, occurs, and the search "jumps" back either to a term preceding the "cut" or to the previous node. An abstract definition of a mechanism that enforces one hypothesis and one-level rectification only, is shown below in Prolog-like terms.

procedure *enforce_one_level_of_rectification*(H, R).

input: H, Hypothesis.

output: R, result. The result can either be - P,
the plan that is solution, or F, the failure flag.

test(H, Diagnosis),
if Diagnosis = ["rectifiable", Violation] **then**
$rectify = \{ rectify_1 \lor rectify_2 \, . \, . \lor rectify_n \}$,
{
{ *rectify*(H, Violation, P_i),
report("P = P_i") $\wedge$ *stop* } \/
fail(rectify)
} \/
{ "cut" $\wedge$ *fail* }.

An AGMPO program is conducted as a Prolog consultation session. Files are read into the working memory, deleted and updated during the session, in accordance with the type of query, as shown in Fig. 1. The solution - the process outline or the circumscribing preform - is written into external files that are readily executable. At this stage the program stops when arriving at the first satisfactory solution. Some of the capabilities and significant shortcomings of the current C-Prolog implementation are elaborated upon in the following chapters.

5. WORKPIECE REPRESENTATION

5.1 General Approach

The scope of the deep-drawing processes contained in the AGMPO system, - axisymmetric workpieces of diameter monotonically decreasing from the orifice down to the bottom, makes CAD and CAM representations and their linking relatively simple. Initially the required part, the input to both the AGMPO system and the ACDP subsystem, is given in its CAD form. The ACDP subsystem that builds a cup which circumscribes the initial part does so by manipulating the CAD representations only. But once the circumscribing cup is produced it is converted into a CAM representation, which is readable by the AGFPO subsystem. Both CAD and CAM representations consist of:

- part (workpiece) name,
- part (workpiece) shape,
- part (workpiece) material,
- managerial requirements, e.g. quantities and delivery date.

As in industrial practice, material specifications are given in an attached list. Thus the main concern of the AGMPO system, as of other APP systems, is with the shape of the part (workpiece). CAD representations of the geometry apply to both the part and the cup while the CAM representation pertains to the cup only. The CAD representation of the part is as a *simple* polygon. The CAD representation of the cup also includes its contour. It is a list of linear and arc segments. The CAM representation of the cup is a concatenation of manufacturable volumetric elements. The representation of the shape, and conversion from CAD to CAM representation and vice-versa, are dwelt upon in the following sections.

5.2 CAD Representation

Since the ACDP deals with axisymmetric parts, the part shape is represented by its cross section. The *cad_description* relation which describes the required part has three arguments. The first is the name of the part, the second is the CAD description of the shape and the third is the material specifications. The part is represented as a simple *polygon* with the vertices given in a counterclockwise sequence, starting from the inner bottommost vertex, as shown in Fig. 1.

5.3 CAM Representation

For axisymmetric parts produced by deep-drawing processes, the products of the intermediate stages and of the process plan, as well as the final workpiece, are described as a concatenation of volumetric *shape elements*. The elements are represented by their *medial* and wall thickness. A complete CAM representation of the workpiece might also include attached form features and non-axisymmetrical shape elements. CAM representation of the workpiece, in any state, is a *frame*:

part(Part_name, Material, Shape, Managerial-Information).

Shape slot Frame is: [OD, Concatenation of volumetric shape-elements].

Volumetric **shape-element** slot frame has the following structure:

[
- Element_name,
- Element_type,
- Wall_thickness,
- 'Element_type' Parameters,
- Recess_radius (Fillet-radius)

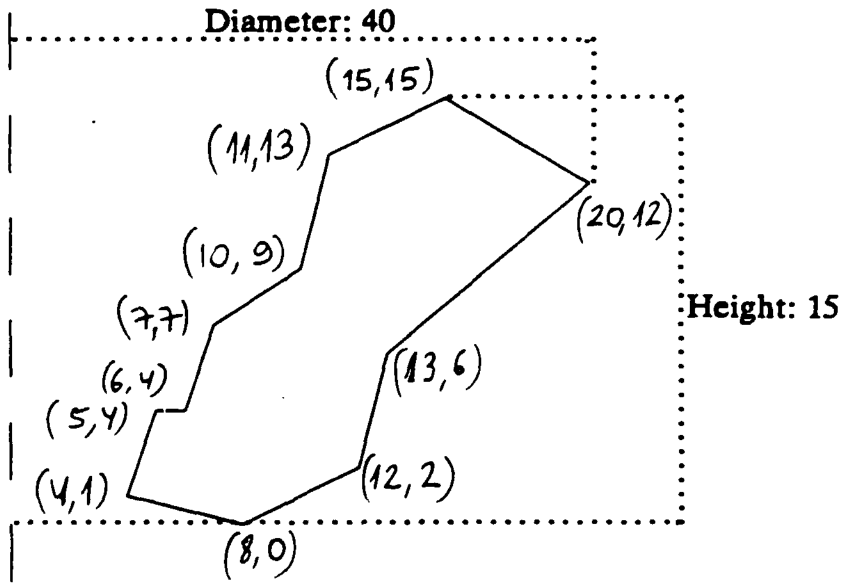
].

The arguments of the frame have the following features:

— Element_name is an arbitrary denotation of the element. It may help in cases where a reader can intuitively correlate the name of the element to

```
cad_description(
        part_1,
        [
         [8,0], [12,2], [13,6],
         [20,12], [15,15], [11,13],
         [10,9], [7,7], [6,4],
         [5,4], [4,1]
        ],
        [SAE 4130, 230 Brinell]
       ).
```

a. Coded representation of a part



b. Part plot

Figure 5-1. A coded representation of a part (*a*) and its plot (*b*)

its location or role.

- Element_type is a code denoting the general form of the element and is taken from Table 3-6.

- Wall-thickness is the thickness of the element.

- Element_type parameters are the values that instantiate the parameters of the specific element type. They are measured w.r.t. the medial and are also given in Table 3-6.

- Each element is assumed to be connected to the adjacent element through a recess arc that is tangential to both. The recess arc is always a part of the "upper" (closer to orifice) element.

Wall-thickness and Element_type parameters are specified in inches or radians. Radians are used only as the first parameter of tapered elements.
The CAM representation is illustrated in Fig. 2.

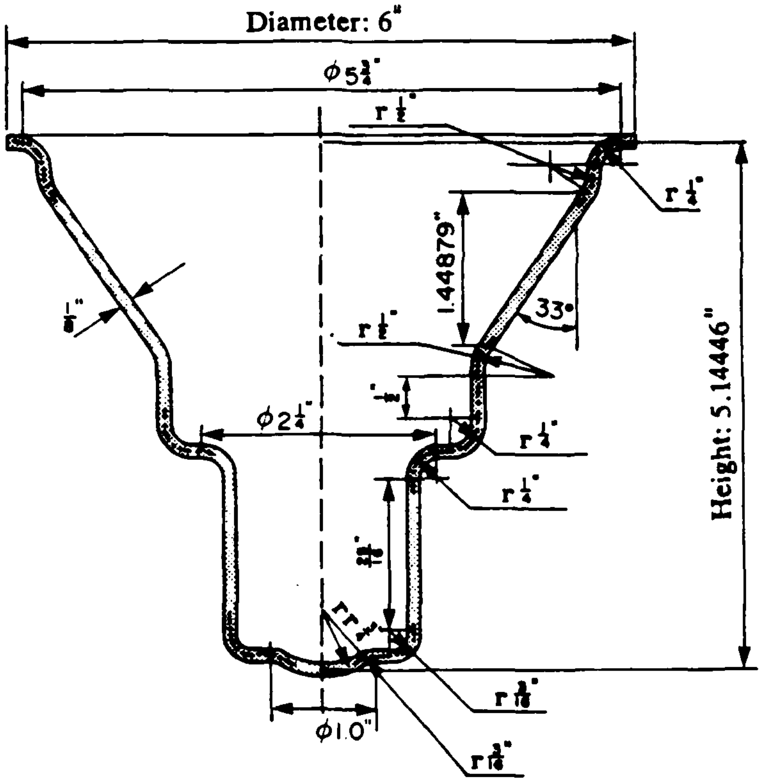
Dimensioning in the above shell is given in such a way that no overlap of sizes takes place but the general pattern of dimensioning does not comply with industrial practice. In industrial practice sizes are introduced with respect to surfaces that facilitate convenient measurement and have some significance w.r.t. subsequent working. This form of workpiece representation constitutes the input to the AGFPO system as well as a description of the de-formed workpiece in intermediate stages. It is also the output of the ACDP system.

5.4 CAD - CAM Links

The scope of finished parts and cups contained in the system, and the type of elements the CAM representation consists of, make the formulation of CAD-CAM links a relatively easy task. In the present study CAD to CAM conversion is sought only for cups. The ACDP subsystem employs it while passing the circumscribing cup to the AGFPO subsystem. The graphic interpreters include a module that converts CAM representations to CAD, to facilitate plotting. In the CAD to CAM conversion, the *skeleton* of the cup is divided into elements that are recognized by the CAM representation, namely main elements of the *element dictionary*, and arcs. The CAM to CAD conversion "plots" the internal and external contours of the cup. Linearization

```
[
 6,
 [ e1, h, 1/8, [23/4], 1/4 ],
 [ e2, v, 1/8, [0], 1/2 ],
 [ e3, a1, 1/8, [0.584894, 1.44789], 1/2 ],
 [ e4, v, 1/8, [1/2], 1/4 ],
 [ e5, h, 1/8, [9/4], 1/4 ],
 [ e6, v, 1/8, [25/16], 3/16 ],
 [ e7, h, 1/8, [1.0], 3/16 ],
 [ e8, r1, 1/8, [3/4, 0.5], 0 ]
].
```

a. Coded representation of a cup



b. Cup plot

Figure 5-2. Coded representation of a cup (*a*) and its plot (*b*)

of arcs is employed to modify CAD representations within the the design of the circumscribing cup. The conversion algorithms presented address only the case where the main element is a (straight) line.

procedure: *CAD to CAM Conversion*:

input: part: a cross-section of a uniform wall-thickness cup and the axis of rotational symmetry. The cross section of a uniform wall-thickness cup is a closed contour built of straight segments and arcs. The straight lines are arranged in parallel pairs and the arcs in concentric pairs. The arcs are tangential to each adjacent straight line segment.

output: cup; a concatenation of volumetric elements.

Uniform wall-thickness is the distance between any two parallel lines.
For all pairs of straight-line segments and concentric arcs *do*:
draw Medial_segment of straight-line segments pair,
with Medial_segment *do*:
match Type_of_segment with available types (Table 3-6),
extract type-parameters from cup sizes.
recess radius = radius of the medial arc of a pair of concentric arcs.

Complexity: : O(n), where n designates the number of straight line elements.

procedure: *CAM to CAD Conversion*:

input: cup; a concatenation of volumetric elements.

output: part: a cross-section of a uniform wall-thickness cup and the axis of rotational symmetry. The cross section of a uniform wall-thickness cup is a closed line built of straight segments and arcs. The straight lines are arranged in parallel pairs and the arcs in concentric pairs. The arcs are tangential to each adjacent straight line segment.

For all elements of cup *do*:

Draw the medial of main element,

Draw the medial of recess arcs,

Draw "internal" boundary: straight line segment and an arc,

at a distance of:

- {half wall-thickness from medial straight-line segment and arc},

Draw "external" boundary: straight line segment and arc,

at a distance of:

+ {half wall-thickness from medial straight-line segment and arc}.

Complexity: : O(k), where k designates the number of components and one component consists of a straight line segments and an arc.

6. GENERATE & TEST and RECTIFY

6.1 G&TR - Main idea

The premise in G&TR is: "Basically, the examined hypothesis is good. If the current plan is infeasible, a plan based on maintaining the *principal* features of the intermediate subgoals should be tried". Other paths that would maintain intermediate subgoals are developed by *refinement* or *amendment* of the route between the initially hypothesized intermediate goals. *Test* in G&TR detects the illegal elements of the plan. The *rectification* procedure modifies the first illegal element. Rectification is pursued such that the initial and *primary properties of the final state* are preserved. Thus, a more accurate but rather lengthy name to "Generate & Test and Rectify" (G&TR) would have been: "Generate & Test then Rectify if needed". As opposed to *G&T, the test* stage of G&TR stipulates a *three-way* possible outcome. The first two diagnoses: *succeed* and *fail*, correspond to those of *G&T*. The third, that singularizes G&TR, is *rectify*. These diagnoses are summarized as follows:

- *Success*: all the operands of the plan/design are fully compatible with requirements, → the plan/design is accepted.
- *Failure*: a *principal* constraint/factor of the plan/design cannot be met.
- *Rectifiability*: a *minor* constraint/factor of the plan/design cannot be met, but some means of overcoming this type of failure are known.

In the context of plan synthesis, G&TR is *nonhierarchical*, although it may be incorporated in a hierarchical planning system, and *evaluation* based, since faith in a hypothesis has to be backed by a highly *evaluational* pattern of building it. (An exploration based procedure yields numerous inexpensive solutions each having slim chances of being accepted, whereas an evaluation based procedure produces fewer candidate solutions, each issued after more deliberations and thus less likely to be rejected. This and other plan synthesis

terms are introduced in Chap. 2.4.3).

G&TR proceeds in two phases. In the first stage a hypothesis is generated. This hypothesis must be tested. If the test succeeds the hypothesis becomes the solution, otherwise either a regeneration or a rectification is invoked. The decision which path to follow is determined by the test. The rectified plan is put to test only if it is generated by a hypothesis-based procedure. This planning process continues recursively.

Before examining G&TR more formally, let us see what would the planning of a journey using a road map look like with it. A route that would be created by the hypothesis generator may be attained in the following manner:

> Choose roads from point **A** in city **a** and point **B** in city **b** that lead to any main highway (such as "State Highway"). Identify a principal highway ("Interstate") that connects the states in which the origin and the destination are located. A *test* would then determine if the two main highways and the interstate road form a route. If they do not, rectify the path by picking a road that joins the State and the Interstate highways. Proceed with these type of rectifications if that link is not found in the first rectification step.

Eventually, some of the applications may be very similar to those produced in hierarchical planning. The difference is twofold: G&TR rectifies one portion of the journey at a time, instead of the whole "layer", and every plan, at the end of each stage, is readily executable if it is valid.

6.2 Abstract Formulation of G&TR

Abstract G&TR (domain-independent) is formally defined G&TR as a tree of procedures. Relationships are stated in terms of *plan* but are applicable to the *design* domain as well. Every procedure is represented by a relationship. Activation of the appropriate relationship by the controlling conflict resolution scheme and the related search mechanisms are discussed later.

procedure $plan(S_I, S_G, P)$ (recursive):

input: initial and final states - S_I and S_G.
output: P - plan to transform initial state to final.

if *generatable*(S_I, S_G, P_i) **then**
{
generate(S_I, S_G, P_i),
test(P_i, Test_Result),
if Test_Result = "succeed" **then** { *report*("P = P_i") $\wedge$ *stop* }
else
{
Test_Result = Violated_action,
if *rectifiable*(S_I, P_i) **then**
rectify_and_test_if_needed(P_i, Violated_action, P)
else *plan*(S_I, S_G, P_{i+1})
}
}
else { *report*("fail") $\wedge$ *stop* }.

Procedure *plan* is the root procedure of G&TR. It proceeds in two phases. In the first phase a new plan is generated, if such a plan is generatable, and tested. The test is especially suited to the specific plan and set of conditions. The test result may be *succeed*, *fail* as in conventional *G&T*, or *rectify*. *rectify* is issued when the *test* figures out that the plan has a chance. The test result diagnosis indicates which action does not meet the test criteria and what are the violated test parameters. This information is abbreviated "Violated_action". *rectify_and_test_if_needed* performs the rectification and decides upon the next planning step, be it "test" or continuation of the evaluation of the rectified plan. The subplan maintains the initial and main final features of the rectifiable portion, and is later embedded into the plan.

procedure *rectify_and_test_if_needed*(S_I, P_I, P_F) (recursive):

input: initial state and plan: S_I and P_I.
output: P_F - final plan.

rectify(P_I, Violated_action, $P_{rectified}$),
if *is_hypothesis_based*(*rectify*(X, Violated_action, Z)) **then**
{
test(P_I, Test_Result)
if Test_Result = "succeed" **then** { *report*($P_F = P_{rectified}$) $\wedge$ *stop* }
else
if *rectifiable*(S_I, $P_{rectified}$) **then**
{ Test_Result = ["Rectifiable", New_Violated_action],
rectify_and_test_if_needed($P_{rectified}$, New_Violated_action, P_F) }
else *fail*(*rectify_and_test_if_needed*(S_I, S_G, P_F))
}
else $P_F = P_{rectified}$.

Rectification planning in *rectify_and_test_if_needed* is tailored to the type of violation. If it is hypothesis-based then a new cycle of *test_and_rectify_if_needed* will be invoked. Otherwise the product of the rectification is inherently valid and can be readily embedded in the plan. Procedure "rectify" performs the rectification of the infeasible portion. The following formulation takes up the an "introduce intermediate operations" rectification approach.

procedure *rectify*(P_I, Violated_action, $P_{rectified}$):

input: initial plan - P_I, and the violated action.
output: $P_{rectified}$ - rectified plan.

Violated_action = [$S_{violated\_action.I}$, $S_{violated\_action.F}$, Rectify_type],
extract_main_features($S_{violated\_action.F}$, $S_{main\_features.F}$),
plan_local($S_{violated\_action.I}$, $S_{main\_features.F}$, Rectify_type, P_{local}),
embed(P_{local}, P_I, $P_{rectified}$).

rectify starts by extracting its planning task from the failed portion of the plan, a job performed by *extract_main_features*. The features of the initial state, and the main independent features of the final state of the violated

element, are set as input to the *plan_local* procedure. *plan_local* plans the transformation of the initial state into the final in a way more refined than its *plan* counterpart, and in most cases is achieved by *forward* reasoning. The very fact that only a part of the main features of the initial final state are extracted and that the planning procedure attempts to satisfy them first, suggests a *planning in phases* pattern. The substitution of the failed portion with the rectified one is performed through the *embed* procedure.

procedure *plan_local*(S_I, $S_{main\_features,F}$, Rectify_type, P_{local})

input: initial and final states - S_I and S_F, and rectification type.
output: P_{local} - new local plan.

extract_main_features(S_I, $S_{main\_features,I}$, $S_{associated\_features,I}$),
plan_fine_plan($S_{main\_features,I}$, $S_{main\_features,F}$, Rectify_type, P_{local_main}),
complete_parameters(P_{local_main}, $S_{associated\_features,F}$),
complete_plan(P_{local_main}, $S_{associated\_features,F}$, P_{local}).

plan_local is a constraint-driven planning procedure. The input is the entire set of initial conditions and the main features of the final state. The dependent final state variables are determined by the resultant plan. The fine-planning procedure that does this work - *plan_fine_plan* - will be assigned a deductive or a forward-reasoning procedure whenever possible. If a deductive reasoning procedure creates the subplan, subsequent test is not required and the very fact that a plan is realized proves that it is valid. Non-independent parameters and state variables are completed in *complete_parameters* and the local plan in *complete_plan*.

6.3 Rule Based Application and Search Aspects of G&TR

"Plan synthesis", "design synthesis" or "expert system" are highly likely to be implemented as rule based systems (RBS). The motive for implementing G&TR as a RBS is no different than with other rule based applications. It is essentially prompted by the natural way the in which knowledge is represented and formalized. The above G&TR procedures are easily transformed into a rule based representation along the following guidelines:

- "procedure *relationship*(Arg_1, Arg_2, ..., Arg_n)
  {set of conditions or operations}"
  is transformed into:
  relationship(Arg_1, Arg_2, .., Arg_n) $\leftarrow$ {set of conditions or operations}

- "**if** A **then** B **else** C" is equivalent to: "$A \rightarrow B \;\wedge\; \neg A \rightarrow C$"
  and transformed into: $\{B \leftarrow A\} \vee C$.

- "A \/ B \/ C \/ .. \/ N"
  The A . . N procedures can be represented in a RBS as arguments of a relationship. The argument X of a relationship *relationship_a*(X) will be instantiated, in accordance with the conflict resolution strategy, to one of the procedures: A . . N, where:

$$\textit{relationship\_a}(X). \;\Big|\; \{\, \textit{relationship\_a}(A) \in KB \quad \textit{relationship\_a}(B) \in KB \quad \bullet \quad \bullet \quad \textit{relationship\_a}(N) \in KB \,\}.$$

- A recursive procedure of the form:

$$\textit{relationship\_a}(A_1, A_2, .., A_m, \text{Out\_arg})$$

if {set of conditions} **then** Out_arg
else { *change_input_arguments*(A_1, A_2, .., A_m, B_1, B_2, .., B_m) $\wedge$
relationship_a(B_1, B_2, .., B_m, Out_arg) }.

is put in the following rule:

relationship_a(A_1, A_2, .., A_m, Out_arg) $\leftarrow$
{ {set of conditions} $\wedge$ Out_arg } $\vee$
{ *change_input_arguments*(A_1, A_2, .., A_m, B_1, B_2, .., B_m) $\wedge$
relationship_a(B_1, B_2, .., B_m, Out_arg) }.

Where the A's designate arguments of the relationship that correspond to input variables, and the B's are modified arguments, set for the new recursive procedure. Out_arg designates the set of output variables.

G&TR is thus described as a tree of procedures in which search aspects are excluded. This notwithstanding, the flow of the procedures and the rule based

application imply the existence of some favorable search and data-base management mechanisms.

a. The sequential execution of *plan, test* and *rectify* steps suggests that search be will reduced if each stage searches the relevant data-base only.

b. The rectification process will be utilized only if there is sufficient evidence that the current plan holds some promise of becoming feasible.

6.4 A Note about Applicability w.r.t. Other Plan Synthesis Tactics

As emphasized above, no one planning strategy and tactics can be considered an ultimate means of planning. Some situations and domains of application may present themselves more suitable to G&TR than to other plan synthesis tactics.

— G&TR is clearly aimed at planning domains that involve one level of detail. It may as well be incorporated in hierarchical planning in each of the layers of abstract planning, or in the final stage that produces nonhierarchical planning.

— Unlike the plan refinement stage in skeletal planning, rectification in G&TR manipulates an instantiated plan. Refinement can be applied before rectification is called, in producing the hypothesized plan.

— Unlike plan amendment, G&TR preserves the main features of the intermediate subgoals of the initial hypothesis.

— Unlike plan amendment, G&TR manipulates different sets of knowledge in the hypothesis creation and rectification stages.

— The application of test and the immediately following rectification is done through forward chaining. Skeletal planning strategies and plan amendment tactics are not restricted to a sequence that corresponds to the physical order.

G&TR is applied in both subsystems of AGMPO: ACDP and AGFPO. Salient features of those rules that make them amenable to manipulation by a G&TR mechanism are discussed in the following section. The discussion is

based upon the deep-drawing knowledge base formulated in Chap. 3.

6.5 G&TR in AGFPO

The basis for implementing G&TR in the deep-drawing domain has already been established by formulating the knowledge into three categories that correspond to the G&TR stages. Each element of these categories is already given in Chap. 3 in the form of a rule and thus the above rule based formulation of G&TR can be readily applied. A G&TR KB should above all have a *rectify* component. The deep-drawing KB has this part and does comply with other essential G&TR properties. The three stages of G&TR are realized in the the deep-drawing KB in the following three categories:

- Generate the hypothesis, - plan the initial sequence of deep-drawing operations. Rules of this category are designated as D Rules.
- Test the workability and realizability of a sequence of deep-drawing operations. The rules here are called: T Rules.
- Rectify the process if a *formability* violation is predicted. These rules are designated as R Rules.

The fourth category, in which computation rules of the first three categories are grouped, is introduced to make the formulation and search more efficient. There are several important structural features of the deep-drawing rules, like the "validity within *scope*" property, that are not necessarily G&TR preconditions and will not be dwelt upon here.

The second G&TR precondition is the three-way outcome of the test stage. Deep-drawing feasibility indeed features this characteristic. Those results have the following meaning:

– *Feasibility*: the sequence of operations is initiated and completed successfully.

– *Infeasibility*: the sequence of operations, or one specific operation, cannot be initiated (incipient flow is not met) or realized (available equipment is inadequate).

– *Rectifiability*: the sequence of operations can be initiated but cannot be successfully completed, i.e. a failure or a defect are predicted.

There are three test categories: { *machine*, *yield*, *defect-develop* } which

correspond to the three-way feasibility outcome of the test stage.

1. The *machine* category which includes the two subcategories:

   { *machine-yield*, *machine-defect-prevention* }

   turns out a "yes" or "no" feasibility result.

   machine-yield contains TRs for the machine capabilities to induce plastic flow; *machine-defect-prevention* contains rules for the machine capabilities to prevent defects.

   For example, **T Rule 38** which is valid within any drawing process domain tests if punch load requirements are satisfied. It states:

   If punch load does not exceed the maximum required drawing force during the drawing **then** the deformation cannot be accomplished.

   If the drawing force is higher than that which the press can develop then the operation is *infeasible* and the hypothesis fails.

2. *failure/defect develop* category can yield both feasibility and rectifiability results. It specifies the flow conditions under which a failure or a defect may occur. If the accumulated imparted strains do not exceed a certain ultimate strain, specific to every material, the deep-drawing KB maintains that it can be rectified. For example: **T Rule 52** states:

   If Conicity severity$_{\text{drawn zone}}$ $\geq$ Limit-Conicity-Severity **then** puckering may occur in the boundary between the conical wall and the die recess rounding.

   This rule is composed knowing that the puckering defect is rectifiable and the result of the rule is of the type: "yes or rectifiable".

3. The *yield* category is a means of determining where and how to test. It is thus an auxiliary category for the main feasibility or rectifiability categories.

   For example, **T Rule 42** which is valid for composite shells and redrawing or stretch-forming processes, determines where to test the representative flow stress. It states:

   If flow-resistance is to be tested **then** it is sufficient to test imparted incipient flow in the orifice of the deformation—zone$_{\text{current}}$.

   It can thus be used by both the *machine* and *defect/failure-prevent* categories.

The characteristic of the deep-drawing KB is that while the design is done by backward planning (de-forming), testing and rectification are likely to be performed forward. This change of strategy stems from the fact that the mechanical properties of the workpiece are constantly changing. A common way of realizing rectification is by introducing intermediate operations that either improve initial mechanical properties or make the strain path less severe. Rectification rules are grouped into categories by the type of violation they are designed to rectify. For example: A *Limit Drawing Ratio* failure is rectified by either employing less severe drawing conditions that would prevent necking, or by improving material properties. Less severe compressive strains can be obtained by introducing intermediate passes or by drawing through a curved (tractrix-shaped) die. Material properties can be changed by heat-treatment. **R Rule 57** pertains to the former type of rectification. It states:

> **If** required Redraw-Ratio is greater than Limit–Redraw–Ratio$_{\text{instantaneous}}$ **then** the introduction of intermediate passes such that each complies with the appropriate Limit–Redraw–Ratio$_{\text{instantaneous}}$ is necessary.

Once this rule is fired it is instantiated with the appropriate **C Rules**, e.g. **C Rule 116**, which gives the limit strains in the form of a table.

The *design* rules (D Rules) are used to generate the hypothesis. They are basically of the type that would be found in G&T based systems. Their main process planning feature is the backwards design. D Rules are organized into three categories according to the role of design they assume. The first design category is unique to the hypothesis stage. The other two are used at the rectification stage too. G&TR features of these categories are as follows:

1. Find the previous *main* shape out of which the current one is likely to be drawn, and the process that can best perform the operation.

   For example:

   D Rule 7

   > **If** shape$_{\text{current}}$ is a cup of one, two or three elements, **then** shape$_{\text{previous}}$ is a circular blank.

2. Design the elements of the *intermediate shape* (designated by main-shape parameters) of the cup that are not determined by the final shape.

   For example:

   D Rule 26

If bend radii of open elements are to be specified **then** they should be designed such that their contribution to additional loads will be minimal.

3. Match the type of the deep-drawing operation and the machine that are capable of performing the transformation.
   For example:
   D Rule 31
   If no blankholder is needed **then** a one-stroke press is sufficient.

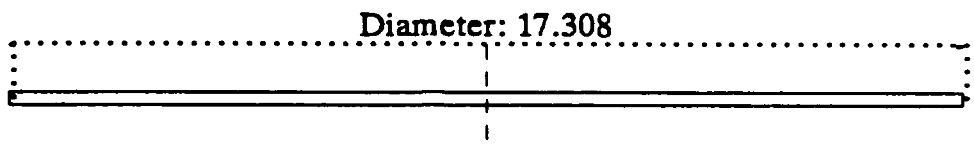
   Once the main previous shape is determined, details of the intermediate shape are designed with the help of rules from design categories II and III.

The application of the G&TR tactics in the AGFPO system proves to be a viable approach for solving complex drawings, but, at the same time, is very sensitive to the initial hypothesis. The presumption in systems that may employ G&TR is that the initial hypothesis is made of basically correct components. The test and rectify portions are intended to locate and improve those components. Although computationally the "test and rectify" component takes up $\simeq 80\%$ of the search space, reactivation of the initial design stretched the system to its computational limits. G&TR is thus most likely to succeed in a regime of nonexhaustive creations of hypotheses.

6.6 A G&TR Example in AGFPO

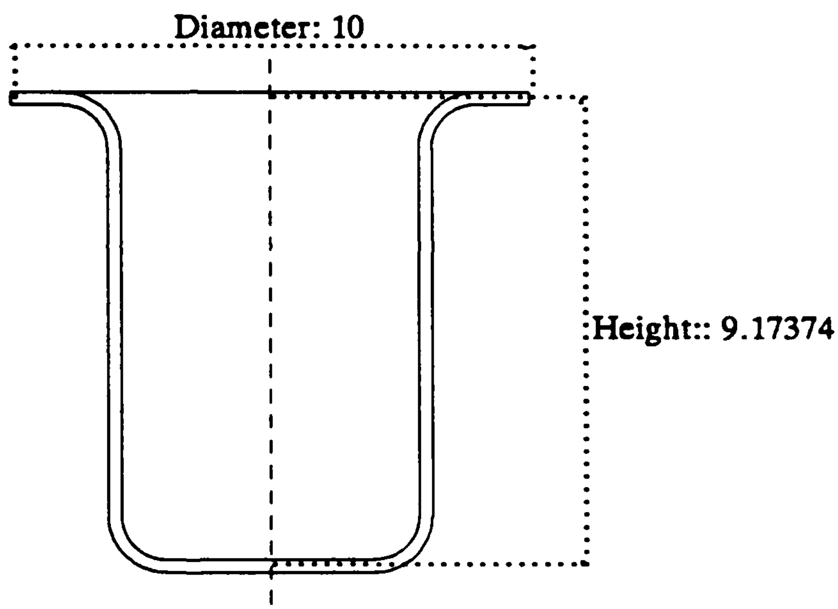
The test and rectify components of G&TR are illustrated in the following example. The way in which the hypothesis is generated is not elaborated upon here. The hypothesized data as shown in Fig. 1.

The redrawing operation is hypothesized to be of a direct redrawing (method *d*) type. The accumulated drawing ratio accounts for the strain history. Suppose the rectification KB is built of **R Rule #57** and **C Rule #116**. The test detected a violation of the limit draw ratio parameter and rectification rule #57 is fired. The basic data for the forward rectification is given in **C Rule 116**. These data have however to be modified in accordance with **C Rules 100 - 109**. Theses rules update the other affecting parameters, e.g. wall thickness and recess radii. The realization of rule 57 determines the



Nominal wall thickness: 0.25

***a*. Initial geometry. Accumulated drawing ratio: 0.**



Nominal wall thickness: 0.25.

***b*. Final geoemtry.**

Figure 6-1. The initial and final geometries of a hypothesized redrawing operation (Material: Austenitic stainless steel)

maximum diameter to which the intermediate cup can be designed. Once this parameter is introduced, the detail design categories (II and III of the design category) are activated to complement the design of the intermediate cup. They determine the recess radii and the type of deformation process. The outcome is schematically described in Fig. 2. It is shown there that two intermediate passes have been inserted between the initial and final states.

The rectified operation, which is actually a local process outline, substitutes the initial operation of the hypothesized process outline, bringing a new strain history with it.

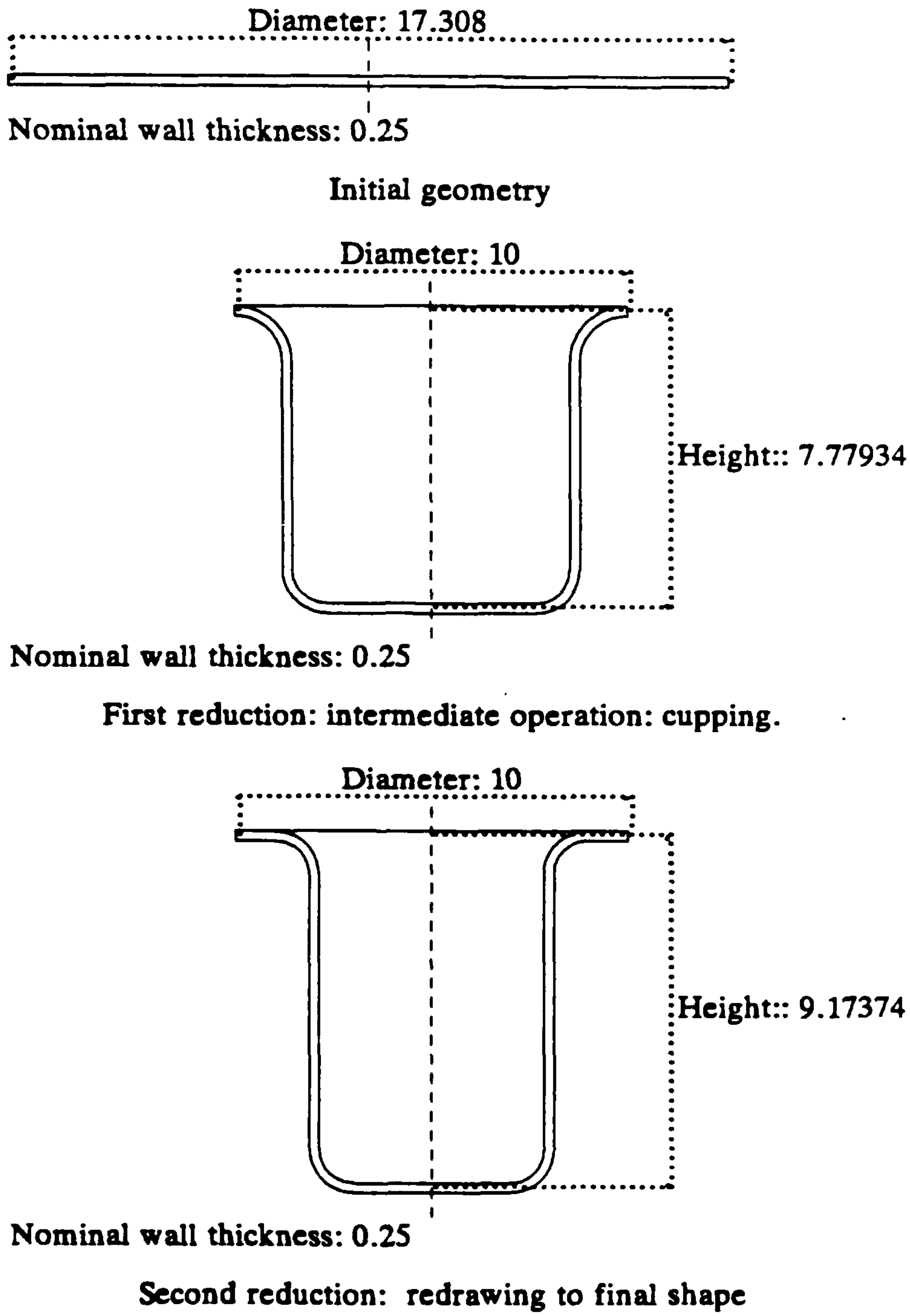


Figure 6-2. Rectified operation

7. PREFORM DESIGN by CIRCUMSCRIPTION

Nomenclature and Definitions

Subscripts:

Cur - Current.

F - final.

G - goal.

H - pertaining to Hypothesis

i - serial numbers

I - initial.

N - New.

Fac - Facing; in context of the determination of the reference surface.

Ref - Reference.

Rem - Remaining.

Special symbols:

$\lceil\rfloor$ - start and end of a procedure.

/* - start of a comment within a procedure.

$\leftarrow$ or $\rightarrow$ - logical imply.

$\wedge$ - logical "and".

$\vee$ - logical "or".

$\{X\}$ - set X.

$[X]$ - list or ordered set X.

$\{\ X\ \}$ - a set of elements X, or a set of procedures X, being processed sequentially. "{" stands for **begin** and "}" for **end**.

$\|$ - parallel.

$O(X)$ - complexity in the order of X.

Definitions and Terminology:

bi-monotonic polygon- a polygon (simple) of four consecutive monotonic chains, bounded by the supporting points of a minimal circumscribing rectangular polygon of two sides parallel to the axis of axisymmetry (see Fig. 1).

cup - the product of a set of deep-drawing processes. A monotonic cup is described in Fig. 2.

orifice - the opening of the cup (see Fig. 2).

instantiate - assign a constant to a variable.

Uninstantiated arguments and variables will be denoted by a name starting with a capital letter.

medial - the skeleton of a geometric body. The thickness centerline in a 2D shape and the thickness center-surface in a 3D shape. The medial of a cup is shown in Fig. 2, in a dashed line.

relationship - *relationship*($V_1, V_2, .., V_n, X_1, X_2, .., X_m$) defines a function that maps *input* variables: $\{V_1, V_2, .., V_n\}$ into *output* variables: $\{X_1, X_2, .., X_m\}$. The *italics* notation for a *relationship*, used a the algorithmic description of procedures are maintained thereafter in the text. A *relationship* is also called *functor* (logic languages) and *relator* (relational algebra and relational databases).

Principal relationships:

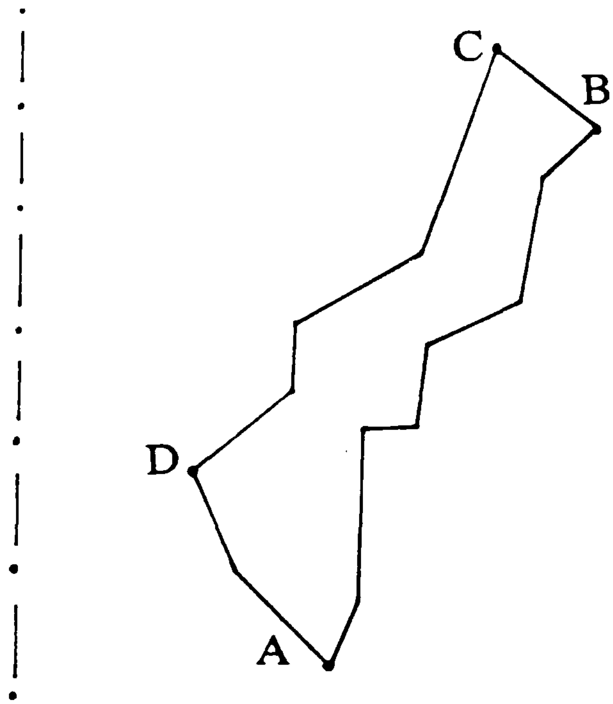
fail(X) - X fails.

generatable(X_I, X_G, D) - for a given initial state X_I and a goal state X_G; a design (solution) D can be generated.

initialize_if_empty(X) - **if** X is empty **then** initialize it, otherwise do nothing.

rectifiable(X_I, X_G, D) - A design D that is designated to transform initial state X_I into goal state X_G and does not meet the requirements, is of the type that can be rectified.

smooth(X, Y) - vertices of a piecewise linear line X are transformed into tangential arcs, yielding smoothed line Y. An example is shown in Fig. 3.



Chain AB: X and Y monotonically increasing.

Chain BC: X monotonically decreasing and Y monotonically increasing.

Chain CD: X and Y monotonically decreasing.

Chain DA: X monotonically increasing and Y monotonically decreasing.

Figure 7-1. A bi-monotonic polygon

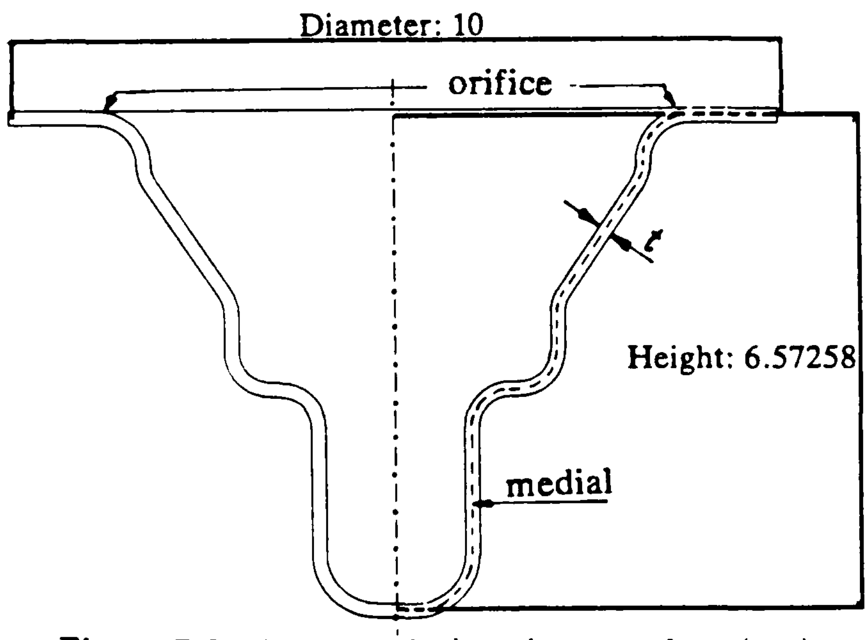


Figure 7-2. A monotonic deep-drawn preform (cup)

smoothable(X) - piecewise linear line X can be transformed into a smoothed line Y with specified range of arc radii. An example is given in Fig. 3.
succeed(X) - X succeeds.

Notations:

For names of *relationships* and variables, when wishing to be as descriptive but aslo as efficient as possible, use some of the following abbreviations:

- Number of ... .
ACDP - Automatic Circumscription by a Deep-drawable Preform.
C - Circumscribing, (C-polygon - circumscribing polygon).
CC - Circumscribing Cup.
CG - Computational Geometry.
cont - abbreviation for "contour" in procedures, e.g. Part_cont - part contour, polygon_cont - polygon contour.
D - Design.
det - determine.
Ext/*ext* - external.
G&T - Generate and Test.
GT - Group Technology.
G&TR - Generate & Test and Rectify.
Head - first element of a list.
Int/*int* - internal.
k - number of elements of the medial of a cup.
KB - Knowledge Base.
n - number of vertices or sides of a simple polygon.
Par/*par* - parallel.
Part - part.
PLL - Piecewise Linear Line.
prep - prepare.
ref - reference.
S - Segment.
Surf/*surf* - surface.
t - wall thickness
Tail - The remaining chain of a list, with the Head removed.

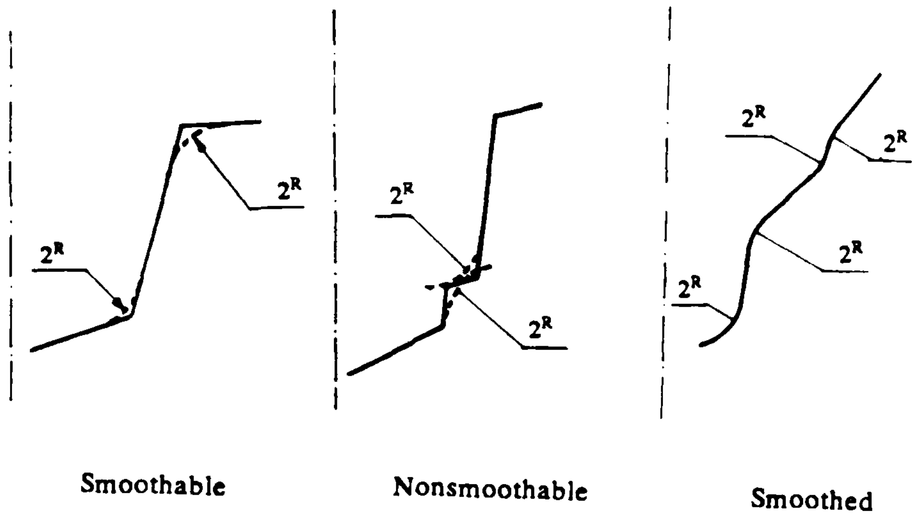


Figure 7-3. Smoothable, nonsmoothable (radius of curvature = 2) and smoothed lines

V - vertex.

7.1 Scope and Problem Definition

ACDP procedure can be viewed as a particular case of a more generalized geometrical circumscription procedure. Its current scope is relatively limited. The part, as well as the circumscribing cup are axisymmetric and bi-monotonic, and in addition, the circumscribing cup is, of uniform-wall-thickness. The circumscription task becomes basically a two-dimensional one, and much simplified. This notwithstanding, more articulated and less restricted automatic preform design procedures are expected to evolve from the same approach, as the principal procedures are adapted to a broader scope. The current scope of ACDP is as follows:

7.1.1 General Observations

— Axisymmetry, of both the part and the preform, implies that it is sufficient to manipulate a planar cross-section of the part and of the circumscribing cup.

— Axes of rotational symmetry of the part and the circumscribing cup are co-linear.

— The inscribed part, and consequently the circumscribing cup, are represented by the RHS of their planar cross section, w.r.t. the axis of rotational symmetry (see Fig. 1).

7.1.2 The Inscribed Workpiece

A general part is shown in Fig. 1. Some of its prominent features are:

— The part is a bi-monotonic polygon w.r.t. the X and Y axes.

— Number of segments constituting the part polygon is denoted n.

— The cross-sectional contour of the part is represented as a concatenation (implemented as list) of segments, starting from the outer bottommost one. The number of segments is denoted n.

7.1.3 Features of A Deep-Drawn Preform

A deep-drawn preform, - *cup* - is shown in Fig. 2. Some of its features, significant in the context of automatic design, are emphasized below:

— The cup is monotonic and of uniform-wall-thickness.

— The nominal wall-thickness of the circumscribing cup is selected from a set of discrete sizes pertaining to the particular material the cup is made of.

— The default circumscribing cup is flat bottomed. A generalized flat-bottomed cup contains dome-bottomed cups by assigning zero diameter to the bottommost element.

— The circumscribing cup is a concatenation of "rings", each being composed of a main element (vertical, horizontal, tapered, etc.) and a recess arc. The recess arc is tangential to the main elements of the current and adjacent rings.

— Number of "rings" the cup is built of is designated k.

— The recess radii have to satisfy some minimum and maximum conditions depending upon material type, mechanical properties and grain structure. The particular values of the recess radii which must be within the technological limits are determined by the goodness-of-circumscription criterion.

— A cup is represented by its medial and wall-thickness, starting from the orifice. The medial is given as a concatenation of segments and arcs.

7.1.4 Goodness-of-Circumscription Criteria

The technological knowledge of deep-drawing is not yet capable of analytically defining an unequivocal objective function and optimality criterion, for a CC design. One obvious deviation stems from the idealization: "uniform wall thickness". In real industrial design, the predicted changes in wall thickness *have* to be taken into account in the design of the CC, constituting thereby a process-planning feedback cycle. Clearly, goodness of the CC should minimize overall cost, subject to design and technological specifications. The cost consists of raw material and the additional work of machining to the required finished geometry. In designing a circumscribing deep-drawn cup, two principal features have to be determined: wall thickness and recess roundings. Were the circumscription a geometrical-only problem, each of these two could provide for adequate circumscription.

The economic rationale for thinner sheets is quite simple: thinner sheets cause less material to be wasted and often offer better uniformity and reliability of mechanical properties. It is analytically proven and empirically corroborated that the effects of the recess radii and wall-thickness depend on *relative* values. Relative recess-radii are determined w.r.t. wall-thickness and cup orifice at the location of the radius, as shown in Chap. 3.4. Relative wall-thickness is significant w.r.t. initial blank diameter, recess radii, cup orifice and edge width - when it constitutes a flange. Recess radii and wall-thickness needed to produce a deep-drawable cup, and effects of changes in their values are outlined below:

Recess-Radii:

— Too small punch-imparted radii (typically: smaller than $2t$) may bring about overthinning and ultimately tear in the draw.

— Too large punch-imparted radii (typically: greater than $10t$) may introduce undesirable stretching in the bend region, with ensuing greater than expected thinning.

— Too small die-imparted radii (typically: smaller than $2t$) increase significantly the bending component of the drawing force. This may require additional drawing passes and may also cause cracks at the bend.

— Too large die-imparted radii (typically: greater than $10t$) increase the susceptibility to puckering (wall wrinkling) since the bent portion is not supported on one side by the punch.

Wall-Thickness:

— Increased wall-thickness adds to material that has to be machined away, i.e. higher cost of raw-material and machining work.

— Thin cups (below a certain critical ratio) are more prone to springback effects, thus making subsequent positioning and finish machining more difficult and at times even impossible.

— Thicker wall-thickness increases the deviation from ideal "plane-strain" deformation conditions. This increases the nonuniformity of mechanical properties and the thinning gradient.

Thinner wall-thicknesses facilitate the attainment of smaller, in absolute value, recess radii. But since it is desirable to increase, up to a certain limit, the relative recess radii, a trade-off between the relative wall-thickness and recess radii is established. Usually the relationship between these relative values is such that containment of a polygon may be achieved with smaller wall-thicknesses but, at the same time, sharper relative recess radii. This finding is schematically shown in Fig. 4.

Some of the uncertainty of the goodness-of-circumscription criteria can be overcome by considering the appropriate properties of the participating manufacturing processes. Per-piece work is relatively high in machining and relatively low in stamping, while the reverse applies to initial costs (set-up). The production mode is related to the goodness-of-circumscription by the following rule: "Machining is preferable in small batches while forming is in large batches". Hence, in small batches a good circumscribing cup will have smaller recess-radii at the expense of increased wall-thickness. In large batches the situation is reversed.

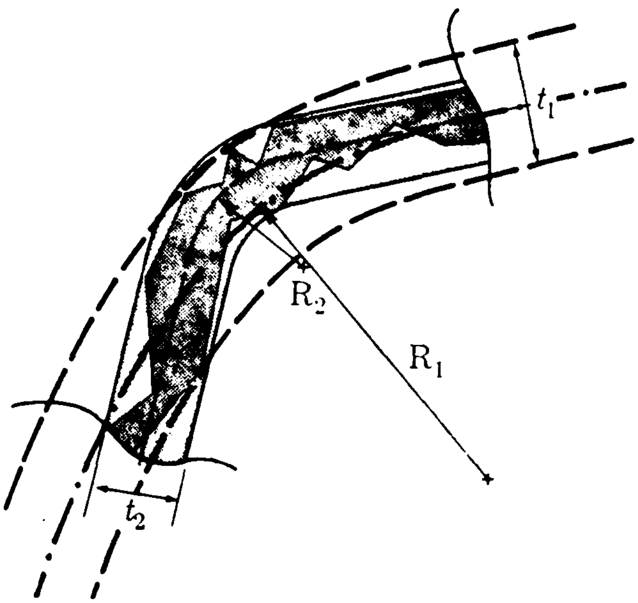


Figure 7-4. Trade-off between wall-thickness and recess radii in a circumscribing cup

7.1.5 Program Parameters

The ACDP can be adapted to the particular factory conditions, through the following inputs:

— The mode of production, which determines if priority is given to machining or stamping.

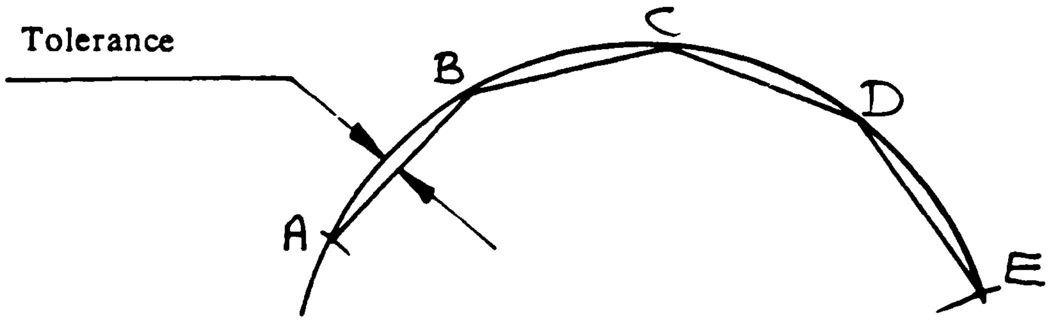
— Circumscription utilizes available raw materials. It can thus be assigned discrete wall thicknesses values of the available stock.

— For both convenience and computational efficiency curved lines like cup roundings are replaced with their PLL approximations. Linearization is not expected to introduce additional significant inaccuracy in the final result. Linearized approximation of curves are specified by the allowed *tolerance* between the curve (arc) and the cord, as shown in Fig. 5.

7.2 Methodology

The automatic circumscription by a deep-drawn preform (ACDP) procedure is presented in a top-down manner and a relationship-like form. In computational geometry terms the problem is formulated as follows:

Given a line, henceforth *axis of rotational symmetry*, and a simple bi-



Line ABCDE $\approx \widehat{AE}$

Figure 7-5. Piecewise linear approximation of an arc

monotonic polygon w.r.t. it, find the uniform width strip that contains the polygon and satisfies the following conditions:

- the distance of each of the elements of the strip from the axis of rotational symmetry is monotonically nondecreasing with one end being perpendicular to the axis of axisymmetry,
- the strip is a concatenation of alternating straight and arcuate bands,
- the arcs are tangential to the adjacent straight line strips,
- the arcs have to be within a certain range defined w.r.t. the width of the strip.

Viewing the design procedures as organized in a tree structure, the bottommost ("leaf") procedures are the significant ones for determining complexity. Search is dealt with whenever a conflict has to be resolved. It is guided by part characteristics and the production mode, which determine the goodness-of-circumscription criterion, or by the predefined structure of the rules. The nature of the problem - each design is concerned with a new product - implies that overall complexity, rather than the decomposition stages of preprocessing (preparing the file for queries) and individual query performances, is the only significant aspect. Factory-dependent knowledge modules, e.g. available wall-thicknesses, are presumed to be part of the global knowledge base. Although some indicative names of arguments, e.g. Part,

$Surf_{Ref}$ and Cup, are maintained in the procedures below, geometric entities rather than their manufacturing meanings are processed. Throughout the procedure, a Prolog like notation w.r.t. variables is preserved: variables are denoted by names starting with capital letters, e.g. Part, Cup, Violated_feature, and instantiated arguments have names starting with small letters or within quotes, e.g. part_a, "succeed". An exception is the denotation of variable wall thickness by t, which will be kept to maintain consistency with preceding text. Recursive calls, when operated on a set of generalized rules, have their first relationship instantiated from the data item following the one the previous call employed.

7.2.1 Algorithm Overview

dddp (Design a Deep-Drawn Preform) is the root procedure of ACDP. It assumes one input: the CAD description of the required part. The environment parameters, that may have been introduced also as variable inputs, are assumed to be keyed in separately, in advance. The top level *dddp* break-up is in fact the application of the G&TR tactic to automatic circumscription. The *generate* stage produces either a full cup or a medial and a minimum wall thickness which constitute a basis for subsequent modifications. For simplicity of presentation, only the case where an initial cup is feasible is discussed. The modifications are heuristic procedures that are utilized when the cup does not contain the part. They attempt make various changes in the smoothing of the medial and the wall thickness of the cup. In the context of the G&TR tactic these modifications are *rectifications.* None of these rectifications is guaranteed to produce a circumscribing cup. Hence the RBS structure provides a proper setting that can be expanded with new smoothing heuristics. Two important rectifications will be later presented.

procedure: *dddp*(Part, Cup_F) (recursive):

input: Part - bi-monotonic polygon.
output: Cup_F - The final circumscribing cup.

□

```
if generatable( Part, Cup_H ) then
  {
    generate( Part, Cup_H ),
    test( Cup_H, Part, Diagnosis ),
    if Diagnosis = "succeed" then {report("Cup_F = Cup_H") ∧ stop }
    else
      {
        if Diagnosis = "rectifiable" then
            {rectify_and_test_if_needed( Cup_H, Cup_rectified )
              ∧ Cup_F = Cup_rectified }
        else dddp( Part, Cup_F ) | KB_next hypothesis
      }
  }
else { report( "fail" ) ∧ stop }.
```

□

search: The *generate* procedure may base the circumscription upon either the internal or the external wall. Currently priority is given to the internal wall, but this preference may be controlled by an input parameter. Flexibility and variety of designs are maintained through variations in *rectify_and_test_if_needed* relationships. A particular relationship is selected from the applicable relationships. This selection process is referred to henceforth as: "conflict resolution" or simply "resolution". Further discussion is deferred to the detailed procedures.

7.2.2 Creating the Hypothesis - The Initial Preform

The hypothesis produces the initial cup, or if that is not directly producible, the *medial* out of which a cup will be attempted, and the minimum wall thickness. The cup is generated by a non-recursive six step procedure. The main idea in *generate* is to first circumscribe the part with a uniform-

wall-thickness polygon. A medial is extracted from that polygon and smoothed later on. The hypothesized cup is specified by the smoothed medial and the wall thickness of the circumscribing polygon. As noted above, only the case where an initial cup is feasible is discussed, for simplicity of presentation.

procedure: *generate*(Part, Cup_H)

input: Part - bi-monotonic polygon.

output: Cup_H - hypothesis about the circumscribing cup.

□

det_surf_of_ref(Part, $\mathrm{Surf}_{\mathrm{Ref}}$, $\mathrm{Surf}_{\mathrm{Fac}}$),

det_t_of_c_polygon($\mathrm{Surf}_{\mathrm{Ref}}$, $\mathrm{Surf}_{\mathrm{Fac}}$, $t_{\mathrm{c\_polygon}}$),

draw_c_polygon($\mathrm{Surf}_{\mathrm{Ref}}$, $t_{\mathrm{c\_polygon}}$, C_polygon),

det_medial(C_polygon, $t_{\mathrm{c\_polygon}}$, Medial),

smooth_medial($t_{\mathrm{c\_polygon}}$, Medial, $\mathrm{Medial}_{\mathrm{smoothed}}$),

const_uniform_t_cup($t_{\mathrm{c\_polygon}}$, $\mathrm{Medial}_{\mathrm{smoothed}}$, Cup_H).

□

search: *det_t_of_c_polygon* is resolved based on the type of $\mathrm{Surf}_{\mathrm{Ref}}$ determined in the previous procedure. *smooth_medial* is an empirical-based heuristic procedure, crucial to the outcome. It is searched and resolved upon part characteristics and predefined ordering.

det_surf_of_ref decides if the hypothesized circumscribing cup will be based upon the internal or the external wall of the part. It is presumed here that unless the external surface is considerably simpler than the internal one, the internal surface is chosen as reference. A simpler surface, i.e. a surface of fewer elements, requires fewer drawing passes. Ramifications for strain paths and economy of deformation are obvious. The rationale for the preference given to the internal wall is:

> The resultant external surface of a drawn cup tends to display significant deviation from the contour of the punch, while the internal surface wraps it and assumes (to a large degree) its exact contour. Thus, if wall-thickness considerations are to be introduced, it is much more helpful to attribute the violations to the external contour.

A more generalized *det_surf_of_ref*, which may create a technologically superior surface of reference that is not necessarily identical to either the internal or

the external contour, is not studied here.

procedure: *det_surf_of_ref*(Part, $\mathrm{Surf_{Ref}}$, $\mathrm{Surf_{Fac}}$)

input: Part - bi-monotonic polygon.

output: surface of reference ($\mathrm{Surf_{Ref}}$) and the facing surface ($\mathrm{Surf_{Fac}}$).

□

extract_polygon_cont(Part, "Internal", $\mathrm{Part\_cont_{Int}}$),

extract_polygon_cont(Part, "External", $\mathrm{Part\_cont_{Ext}}$),

if $\#\_\mathrm{elements}_{\mathrm{Part\_cont_{Int}}} > \frac{1}{3}\#\_\mathrm{elements}_{\mathrm{Part\_cont_{Ext}}}$ **then**

$\mathrm{Ref} = \mathrm{Part\_cont_{Int}}$

else $\mathrm{Ref} = \mathrm{Part\_cont_{Ext}}$.

□

complexity: O(n), - Part is represented as a list of n straight-line segments. The number of elements in that list is counted and mapped into two new lists.

To simplify formulation of procedures henceforth, it is stipulated that the $\mathrm{Surf_{Ref}}$ is the internal wall.

det_t_of_c_polygon assumes a structure of a *uniform wall thickness* polygon. A uniform-wall-thickness polygon is a "truncated union" of beams of the same wall-thickness, as shown in Fig. 6.

The building of the uniform wall thickness polygon draws on the property of the boundary between two adjacent "beams" being a *bisector*. The surface of reference, $\mathrm{Surf_{Ref}}$, from which the wall-thickness is measured, is scanned segment by segment, to find the maximum wall thickness w.r.t. each of the segments. "Region" is the list of vertices (V's) on $\mathrm{Surf_{Fac}}$ contained between bisectors drawn from the ends of the one segment determining that region in $\mathrm{Surf_{Ref}}$. The maximum wall-thickness is the largest distance of a line, contained between those bisectors, from the reference segment S. The largest distance should be allocated from one of the vertices of $\mathrm{Surf_{Fac}}$. This procedure is outlined below and illustrated in Fig. 7.

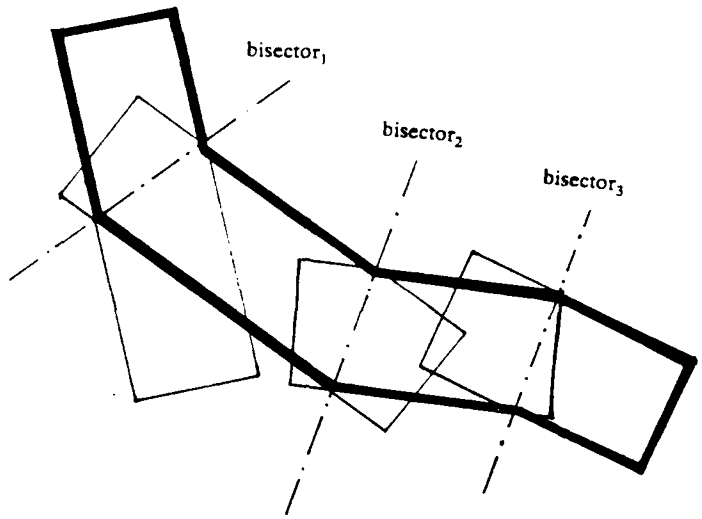


Figure 7-6. A uniform-wall-thickness polygon as a 'truncated union' of uniform-wall-thickness beams

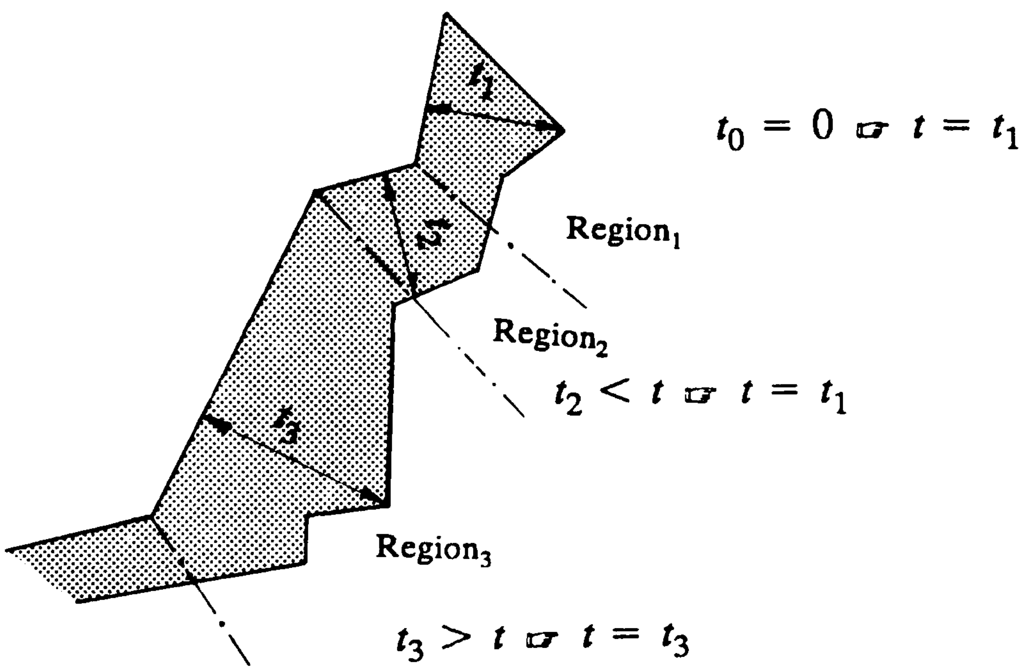


Figure 7-7. Three cycles of determining the wall-thickness of a circumscribing polygon

procedure: *det_t_of_c_polygon*(Surf_{Ref}, Surf_{Fac}, $t_{\text{c\_polygon}}$) (recursive):

input: Surf_{Ref} and Surf_{Fac} two monotonic, non-intersecting PLLs, w.r.t. axis of rotational symmetry.

output: $t_{\text{c\_polygon}}$ - wall-thickness of the circumscribing polygon.

□

initialize_if_needed(t_{Cur}), /* set t_0 */

$\text{Head}_{\text{Surf}_{\text{Ref}}} = \text{S}$,

det_region_to_check_t(Surf_{Fac}, S, Region),

find_max_distance_from_segment(S, Region, $\text{Distance}_{\text{Max}}$),

if $\text{Distance}_{\text{Max}} > t_{\text{Cur}}$ **then** $t_{\text{N}} = \text{Distance}_{\text{Max}}$

else $t_{\text{N}} = t_{\text{Cur}}$,

if *not(is_empty_list*($\text{Tail}_{\text{Surf}_{\text{Ref}}}$)) **then**

{

set_remaining_fac_surf(Surf_{Fac}, Region, $\text{Tail}_{\text{Surf}_{\text{Fac}}}$),

det_t_of_c_polygon($\text{Tail}_{\text{Surf}_{\text{Ref}}}$, $\text{Tail}_{\text{Surf}_{\text{Fac}}}$, t_{N})

}

else { $t_{\text{C-polygon}} = t_{\text{N}} \wedge$ *stop* }.

□

complexity: O(n). Each vertex in Surf_{Fac} is scanned, once only, to find its distance from a particular S. Hence the number of segments from which the distance is measured, and of the vertices on the facing line is exactly n.

draw_c_polygon constructs the uniform wall-thickness polygon. Although it is eventually possible to obtain CC without the uniform wall-thickness circumscribing polygon, *draw_c_polygon* enables one to visualize the procession of the design stages and check the resultant uniform-wall-thickness circumscribing polygon graphically. This procedure is presented below.

procedure: *draw_c_polygon*($Surf_{Ref}$, $t_{c\_polygon}$, C_polygon) (recursive)

input: $Surf_{Ref}$, $t_{c\_polygon}$.

output: C_polygon - the uniform wall-thickness circumscribing polygon.

□

initialize_if_empty(C_polygon). /* initial C_polygon = empty list */

$Head_{Surf_{Ref}} = S$.

draw_parallel(S. S_{Par}).

$S_{Par} || S_i \wedge S_{Par}$ contained in [$Bisector_1 \div Bisector_2$])

erase_segments_intersecting$\wedge$*left_of*(S_i, C_polygon, $C\_polygon_N$),

if *(not (is_empty_list*($Tail_{Surf_{Ref}}$)) **then**

draw_c_polygon($Tail_{Surf_{Ref}}$, $t_{c\_polygon}$, $C\_polygon_N$)

else { C_polygon = $C\_polygon_N$ $\wedge$ *stop* }.

□

complexity: $O(n)$. k, the number of elements of the cup, is determined by the number of segments in $Surf_{Ref}$. Thus: $k < n$, and k is of $O(n)$. The set of erased segments in one cycle has to be a chain of the last j segments, where $j<k$. Thus, at most, $2k$-2 segments can be scanned to be erased.

The process of drawing the uniform wall-thickness polygon and the circumstances of erasing an element are schematically illustrated in Fig. 8.

The medial (the initial medial) is extracted from the uniform-wall-thickness polygon. It is smoothed thereafter. Two algorithms for obtaining the medial were studied:

1. Triangulate the circumscribing polygon and draw the medials of the triangles, each medial being parallel to one of the bases. The bases are segments on either the external or internal wall.
2. Draw a polygon of uniform wall-thickness of $t_{C\_polygon}/2$ w.r.t. the reference surface ($Surf_{Ref}$). The medial is the resulting $Surf_{Fac}$.

Although the resulting medials of the two methods are slightly different, the second approach, which makes use of the already defined *draw_c_polygon* procedure is adopted (for simplicity considerations) and is not further elaborated upon.

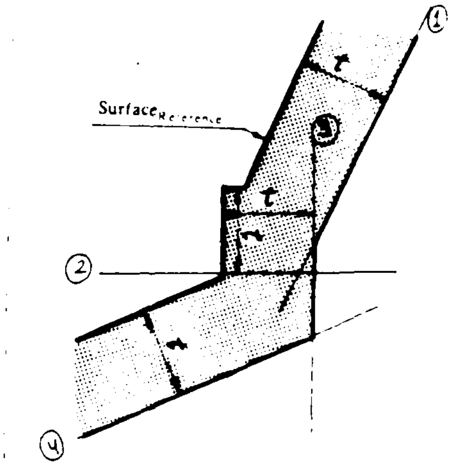


Figure 7-8. Four cycles in constructing the uniform wall-thickness polygon

As noted above, *smooth_medial* is a crucial heuristic in the overall *dddp* algorithm. It produces the designated skeleton (medial) of the circumscribing cup. Once a medial becomes smoothable, the actual smoothing is pursued sequentially, in the *smooth_smoothable_medial* procedure. The first stage modifies the PLL medial so that success in subsequent smoothing is guaranteed. The generation of a smoothable medial is attempted below by several heuristics that try different ways of modifying a non-smoothable PLL. *smooth medial* is a non-recursive two-stage procedure:

procedure: *smooth_medial*(t, Medial, $\text{Medial}_{\text{smoothed}}$)

input: t, wall-thickness of the designated CC and Medial, a PLL.
output: $\text{Medial}_{\text{smoothed}}$ - a line made of straight-line segments joined by tangential arcs.

□

make_medial_smoothable(t, Medial, $\text{Medial}_{\text{smoothable}}$),
smooth_smoothable_medial($\text{Medial}_{\text{smoothable}}$, $\text{Medial}_{\text{smoothed}}$).

□

The *make_medial_smoothable* heuristics create a medial that is smoothable and likely to contain the part. None of them, however, guarantees circumscription. *make_medial_smoothable* modifies the initial medial by means of deleting vertices and or substituting vertices with new ones. The various

algorithms differ from each other in the choice of vertices to be deleted and the introduction of new vertices.

The two principal approaches are:

- "erase intermediate vertices" and
- "discard exceedingly small segments of the medial".

The "erase intermediate vertices" designates a deletion of vertices that cannot be smoothed. The procedure that does it, *make_chain_smoothable*, deletes one or two vertices at a time.

The "discard exceedingly small segments of the medial" substitutes non-smoothable vertices by the vertex which is the intersection of the two adjacent segments.

The *make_medial_smoothable* procedure, which employs the varying *make_chain_smoothable* procedures, is presented below. In this procedure, the first three segments are tested for smoothability. If they are smoothable, the procedure continues recursively, evaluating the last two segments and the adjacent new one. Otherwise, one or two vertices are deleted, and the procedure continues recursively from the beginning of the manipulated portion. If regeneration is reactivated, *make_medial_smoothable* will be backtracked to, and new smoothable medial will emerge from that node.

procedure: *make_medial_smoothable*(t, Medial, $\text{Medial}_{\text{smoothable}}$) (recursive)

input: t - wall-thickness and Medial, PLL.

output: $\text{Medial}_{\text{smoothable}}$ - a PLL that can be smoothed.

```
Medial = [ Test_chain, Tail_Medial ],
Test_chain = first three segments of Medial, starting from orifice,
if not( smoothable( Test_chain ) then
  {
    make_chain_smoothable( Test_chain, Test_chain_smoothed ) ∧
    substitute( Test_chain_smoothed, Test_chain, Medial_updated )   ∧
    make_medial_smoothable( t, Medial_updated, Medial_smoothable )
  }
else
  {
    {
      if not( is_empty_list( Tail_Medial ) ) then
        {
          Medial_Rem = Medial, with first two segments subtracted   ∧
          make_medial_smoothable( t, Medial_Rem, Tail_Medial_smoothable )   ∧
          append( Test_chain, Tail_Medial_smoothable, Medial_smoothable )
        }
      else    Medial_smoothable = Tail_Medial
    } ∧ stop
  }.
```

search: There are several *make_chain_smoothable* procedures. Applicable procedures comply with the desirable "wall-thickness - recess-radii" trade-off and the selection from among the applicable ones is based on the order of those procedures in the KB.

complexity: $O(k)$. At most k-2 vertices will be deleted and $3k$-2 vertices will be tested.

smoothable is the test employed by *make_chain_smoothable* to check if a PLL of three segments is smoothable. *smoothable* checks if the *minimum* recess radii, which is determined by the wall-thickness, can be applied to the chain of segements. It is realized in constant time (independent of the number of segements or their features).

procedure: *smoothable*(Test_chain)

input: Test_chain - a list of four consecutive vertices.
output: diagnosis if Test_chain is smoothable or not.

□

Test_chain = [V_1, V_2, V_3, V_4],
M_point_1 = Median_point of [V_2, V_3],
M_point_2 = Median_point of [V_3, V_4],
smoothable_vertex(V_2, V_1, $V_{M\_point\_1}$) $\wedge$
smoothable_vertex(V_3, $V_{M\_point\_1}$, $V_{M\_point\_2}$).

□

The idea of smoothing a vertex by validating that its neighbors are smoothable, which is realized in *smoothable_vertex*(V_3, $V_{M\_point\_1}$, $V_{M\_point\_2}$), is illustrated in Fig. 3 above and in Fig. 9.

Non-smoothable test_chains are smoothed by the *make_chain_smoothable* heuristics. One version of the "erase intermediate vertices" smoothing method is outlined below and shown in Fig. 10. The "discard exceedingly small segments of the medial" method is outlined in Fig. 11.

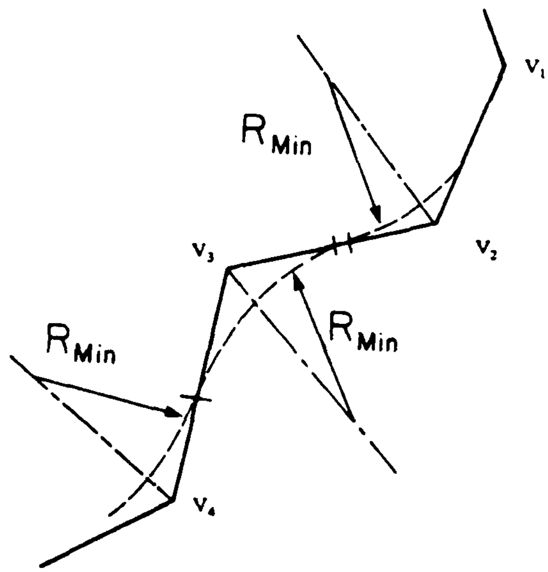


Figure 7-9. Smoothability of a vertex

procedure: ***make_chain_smoothable***(Test_chain, Test_chain$_{smoothable}$)
method: - "erase intermediate vertices"

input: Test_chain - four consecutive vertices.

output: Test_chain$_{smoothable}$ - the modified Test_chain.

□

Test_chain = [V_1, V_2, V_3, V_4],
Cand_chain$_1$= [V_1, V_3, V_4],
Cand_chain$_2$= [V_1, V_2, V_4],
Cand_chain$_3$= [V_1, V_4],
if *smoothable*(Cand_chain$_1$) **then** Test_chain$_{smoothable}$ = Cand_chain$_1$
else
if *smoothable*(Cand_chain_2) **then** Test_chain$_{smoothable}$ = Cand_chain$_2$
else Test_chain$_{smoothed}$ = Cand_chain$_3$.

□

complexity: O(Constant).

The actual smoothing of a smoothable medial, which ends the hypothesis stage, is executed by *smooth_smoothable_medial*. In the smoothing process

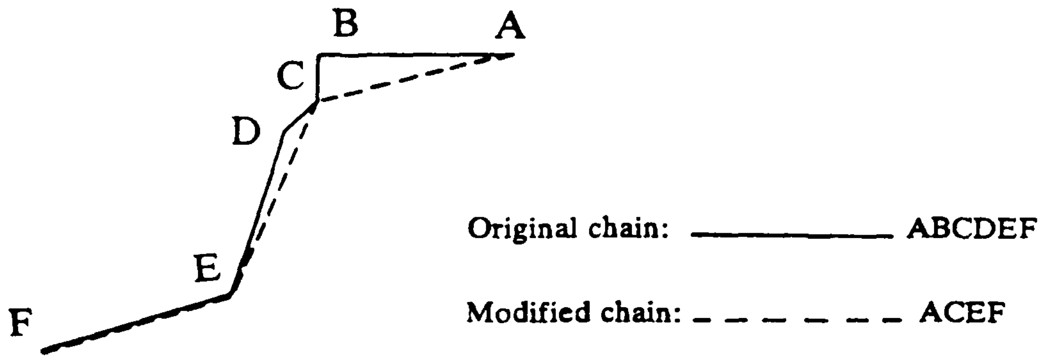


Figure 7-10. Making a chain smoothable by 'erase intermediate vertices'

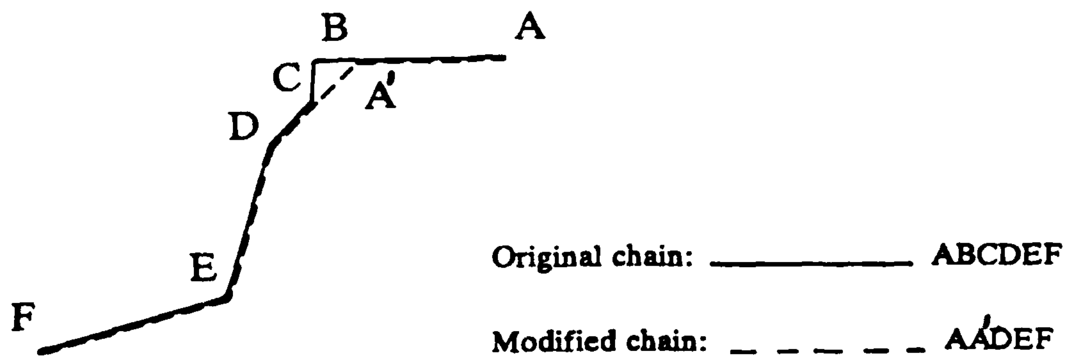


Figure 7-11. Making a chain smoothable by 'discard exceedingly small segments of the medial'

each *vicinity* of a vertex is substituted with an arc. The arc is either of the *largest allowed* recess radius (preferably) or the minimum recess radius. The preference given to the largest allowed radius is in conformance with the technological fact that the larger is the recess radius the smaller are the required bending force and the induced strain-hardening. Thus a cup produced at the hypothesis stage can have its recess radii modified by the same procedure that is later used at the rectification stage.

The drawing of the cup through *const_uniform_t_cup* is a sequential plotting task that is carried out in O(k) time, for a medial of k sides and k-1 arcs.

7.2.3 Testing Circumscription and Directing Rectification

ACDP tests *containment* only. A CC fully contains the part if its cross-sectional contour does not intersect the cross-section of the part. Containment includes *support*, i.e. the vertices of the part may be *supported* by the circumscribing cup. Intersection may be tested by two methods.

intersect (version 1) is an extension of a conventional algorithm: Each segment of the inscribed polygon is checked for intersection with the contour of the CC. Two relaxations due to the monotonicity of the CC are introduced here.

a. Since the polygons are simple it is sufficient to check for intersection of the internal walls of Part and CC separately from the external walls.

b. A division into *beams* can be introduced, thereby constraining the search for intersection within one beam.

intersect (version 2) finds out the wall-thicknesses of two new polygons:

– Polygon_1 = [External-wall-of-Part, Medial], and

– Polygon_2 = [Internal-wall-of-Part, Medial],

and equates it with $t_{c\_polygon}$. If either the wall-thickness of Polygon_1 or Polygon_2 is greater than half the wall-thickness of the circumscribing cup, an intersection does occur.

Complexity-wise both versions display $O(k)$, assuming the CC can be linearized to $O(k)$ segments in linear time.

procedure: *intersect*(Cup, Part):
(version 1, check each beam)

input: Cup (medial and wall-thickness), and Part - a bi-monotonic polygon.
output: Diagnosis if Cup and Part intersect.

$\Box$

extract_polygon_cont(Part, "Internal", $\text{Part\_cont}_{\text{Int}}$),
extract_polygon_cont(Part, "External", $\text{Part\_cont}_{\text{Ext}}$),
create_cont(Medial, $+{}^1\!/_2 t$, $\text{Cup\_cont}_{\text{Int}}$),
create_cont(Medial, $-{}^1\!/_2 t$, $\text{Cup\_cont}_{\text{Ext}}$),
make_beams($\text{Part\_cont}_{\text{Int}}$, $\text{Cup\_cont}_{\text{Int}}$, $\{ S_{\text{Part\_cont}_{\text{Int}}}, \text{PLL}_{\text{Cup\_cont}_{\text{Int}}} \}$),
make_beams($\text{Part\_cont}_{\text{Ext}}$, $\text{Cup\_cont}_{\text{Ext}}$, $\{ S_{\text{Part\_cont}_{\text{Ext}}}, \text{PLL}_{\text{Cup\_cont}_{\text{Ext}}} \}$),
with all beams i (internal), j (external) *do*
  if (*intersect_within_beam*(Beamsibi, $\{ S_{\text{Part\_cont}_{\text{Int}}}, \text{PLL}_{\text{Cup\_cont}_{\text{Int}}} \}$) $\vee$
    intersect_within_beam(Beamsibj, $\{ S_{\text{Part\_cont}_{\text{Ext}}}, \text{PLL}_{\text{Cup\_cont}_{\text{Ext}}} \}$)) **then**
      true(intersect(Cup, Part))
  else *fail(intersect*(Cup, Part)).

$\Box$

complexity: O($n$log$n$), dominated by *make_beams*, the procedure that builds the set of beams and the PLLs of the cup contained within each beam.

procedure: *intersect*(Cup, Part):
(version 2, polygons of part contour and medial)

input: Cup (medial and wall-thickness), and Part - a bi-monotonic polygon.
output: Diagnosis if Cup and Part intersect.

□

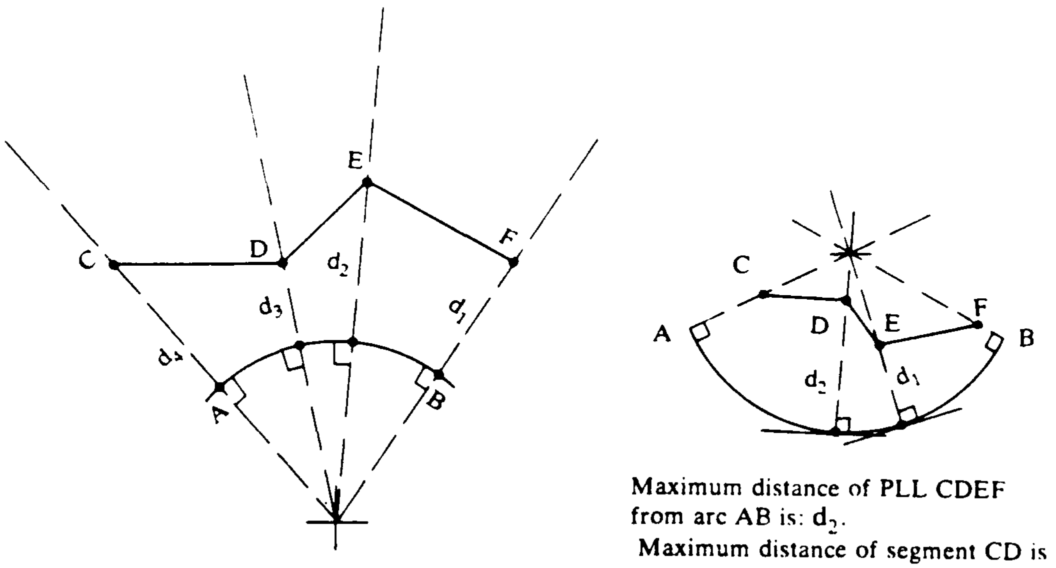
extract_polygon_cont(Part, "Internal", $\text{Part\_cont}_{\text{Int}}$),
extract_polygon_cont(Part, "External", $\text{Part\_cont}_{\text{Ext}}$),
linearize(Medial, Tolerance, Linearized_medial),
$\text{Polygon}_{\text{Int}}$ = [$\text{Part\_cont}_{\text{Int}}$, Linearized_medial],
$\text{Polygon}_{\text{Ext}}$ = [$\text{Part\_cont}_{\text{Ext}}$, Linearized_medial],
det_t_of_c_polygon(Ext_Part_cont, Linearized_medial, $t_{\text{Polygon}_{\text{Int}}}$),
det_t_of_c_polygon(Int_Part_cont, Linearized_medial, $t_{\text{Polygon}_{\text{Ext}}}$),
if $(t_{\text{Polygon}_{\text{Int}}} > \frac{1}{2} t_{\text{C\_polygon}} \vee t_{\text{Polygon}_{\text{Ext}}} > \frac{1}{2} t_{\text{C\_polygon}})$ **then**
true(intersect(Cup, Part))
else *fail(intersect*(Cup, Part)).

□

complexity: O(n), dominated by *det_t_of_c_polygon.*

Each of the *intersect* procedures can be expanded to find the wall-thickness at the intersection. Once again a "region" of vertices contained between two bisectors is built and the largest distance from each of the medial segments becomes half the minimum wall thickness. Whereas determination of the distance between a straight line segment and a PLL is straight-forward (see *det_t_of_c_polygon* above), the distance between an arc and a PLL requires some elaboration.

The arc can be concave or convex, w.r.t. the PLL. If the arc is convex the largest distance is found on the line connecting each of the vertices and the center of the arc, as shown in Fig. 12*a*. Otherwise the maximum distance is either the length of the segment connecting the vertex and the arc along the radius or the distance of the straight line segment from a tangent parallel to the segement, as shown in Fig. 12*b*. The importance of determining the wall thickness if intersection is detected is dwelt upon in the next section.



Maximum distance of PLL CDEF from arc AB is: d_4
Distance is measured at ends of segments.

Maximum distance of PLL CDEF from arc AB is: d_2.
Maximum distance of segment CD is d_2
Maximum distance of segment DE is d_2
Maximum distance of segment EF is d_1

a. arc is convex w.r.t. PLL *b.* arc is concave w.r.t. PLL

Figure 7-12. Distances of a piecewise linear line from an arc

7.2.4 Rectifying a Rejected Cup

An integral part of the test stage is the diagnosis of rectifiability and guidance as to what rectification measures are applicable. As shown above, rectifiability is sought if containment is not met. ACDP rectifications are two-fold. The first level is independent of the diagnosis as to which rectifiability to pursue. It employs the first available set of rectification rules in the KB. Once a set of rectification rules has failed, the inference machine "marks" it so that the next call will fire the next set of rectification rules. The second level employs different smoothing parameters: wall thickness and recess radii. As for increasing wall-thickness, a maximum allowed ratio: $\frac{\text{wall-thickness}}{\text{Diameter}_{\text{Blank}}}$ (typically: $^1/_{10}$) is checked. $\text{Diameter}_{\text{Blank}}$ is twice the square root of the sum of the areas of the elements of the medial and is computed in $O(k)$ time. Reduction of the recess radii of a vertex of the part that intersects the examined cup (say V_i) has a lower bound. Typically, that boundary is determined by $\frac{\text{Recess-Radius}_i}{\text{wall-thickness}}$ and is $\simeq 2$. The check of this ratio for each rounding is computed in constant time.

A rectification procedure rectifies a rejected cup that may be a product of either a hypothesis phase or of a previous rectification. Priorities in utilizing rectifications of the medial-modifying level are predefined by their organization in the knowledge base. The smoothing rectifications are done to suit the specified type of production (small batch - priority is given to increasing the wall thickness, otherwise to reducing the recess radii) in accordance with the wall thickness at the intersection. A rectification procedure that increases the wall-thickness of the entire cup requires a simultaneous adaptation of the recess radii to meet the recess-radius/wall-thickness ratios. A typical *rectify* procedure that increases wall-thickness only if it is available or else the rectification fails, is shown below. There is no guarantee that this procedure or any other *rectify* procedure will produce a formable cup. The effect of increasing wall thickness without changing recess radii is illustrated in Fig. 13.

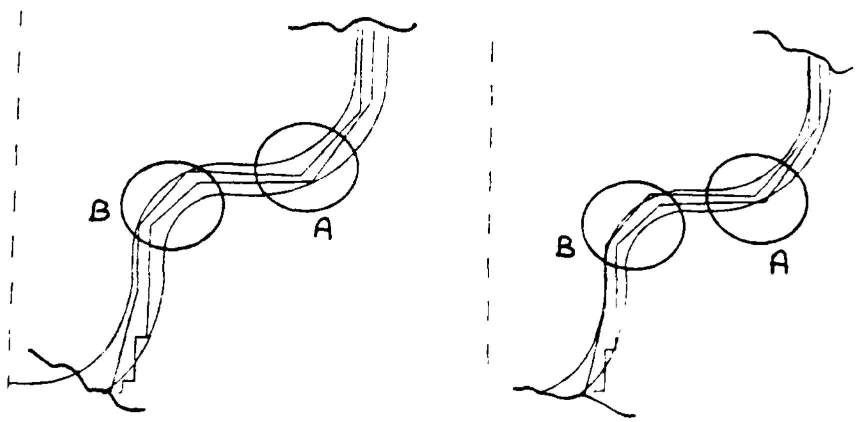


Figure 7-13. Increase in wall thickness to contain a vertex

procedure: *rectify*(Part, Cup, Measure, t_{min}, $Cup_{Rectified}$)

input: Part - a bi-monotonic polygon. Cup - a smoothed medial and the initial wall-thickness, "Measure" which is instantiated in this procedure to "increase wall-thickness", and the minimum new wall thickness t_{min}.
output: $Cup_{Rectified}$, denoted by the new medial wall-thickness.

$\square$

create_polygon_cont(Part, "Internal", $Part\_cont_{Int}$),
create_polygon_cont(Part, "External", $Part\_cont_{Ext}$),
Cup = [Medial, t],
$t_N = min\{ t_{\text{available stock}} \} \wedge t_{\text{available stock}} \geq t_{min}$,
$\forall$ i for $\dfrac{\text{Recess}-\text{radius}_i}{t_N} > \text{Thickness}-\text{Ratio}_{Min}$ *do*

if *increasable*($\text{Recess}-\text{radius}_i$) **then**

{

increase_recess_radius($\{t_N \times \text{Thickness}-\text{Ratio}_{Min}\}$, $Recess\_radius_N$),
modify_cup_structure(Cup, $Recess\_radius_N$, $Cup_{Rectified}$)

}

else "cut", *fail*(*rectify*(Part, Cup, Measure, t sub min,$Cup_{Rectified}$)).

$\square$

complexity: O(n).

The "cut" does not allow backtracking, branching from this rectification rule, once a diagnosis that the recess radius cannot be increased is reached.

Performance and Computational Aspects

Most of the procedures outlined above are programmed in the ACDP system. The system is written in Prolog and runs on the UNIX system at Purdue University. Once presented with a question of the form: "what is the circumscribing deep-drawn-type preform that contains workpiece_X" it automatically invokes the fully automatic circumscription program. Technological design rules upon which recess-radii and wall-thickness relationships are defined are modeled in Chap. 3. A rule given there in the form of:

– "**if** a recess radius has to be introduced **then** it has to be within the range [A,B], with best value being B"

is interpreted to:

- "**if** a recess radius has to be introduced **then** it is going to assume the value B. If that is not possible, it is going to assume the value closest to B that is greater than A."

The rule based formulation which could have been avoided for the hypothesis part is fully justified in the rectification phase. The supervisory G&TR control tactic fires rectification rules in the order they are in knowledge base. This brings, however, the search space many times to explosion, unless the "cut-fail" mechanisms efficiently terminate unfruitful searches. Hence these mechanisms have to be located in the "rectify" procedures so that "first degree" rectification only are allowed. This means that if a rectification fails, next rectification will start from the cup with which the rectification started originally from, and not backtrack up along the failed rectification sequence.

8. AUTOMATIC GENERATION of the INCLUSIVE TEST RULE

8.1 Automatic Testing and the Problem Solving Tactics

An automatic plan (or design) synthesis system based on G&T requires that the "test" component be automatic too. The test in a G&T system usually comes to assess feasibility of the plan (or design) rather than the goodness of solution. The test problem is two-fold: first the appropriate test has to be constructed and then the test has to be carried out.

A simple test procedure within a G&T system implies that a fixed, predefined, test will test any generation result. The problem becomes more complicated when the appropriate test has to be selected out of a set of tests. One step higher in complexity involves the construction of a *composite* test. A composite test is a combination of the applicable individual tests. It is named henceforth: "the inclusive test" since it includes several individual tests. A system for the automatic generation of the inclusive test rule is suitable for a particular structure of the set of individual tests and a certain structure and semantics of each of the individual tests. A system for the *Automatic Generation* of the *inclusive Test-Rule* - AGTR - that suits the technological knowledge of forming processes, deep-drawing included, is described hereby.

The inclusive test that determines if a hypothesis is true has, when applied in the process planning domain, the form of a *conjunction* of tests. This conclusion is derived from the study of the technological knowledge. It emanates from the *independence* of the test rules (true in most cases), - since every test evaluates a particular *test parameter* (T-P), that satisfying the inclusive test boils down to satisfying each of the *applicable* TRs. Since each test is the antecedent part of an individual test rule (TR), the inclusive test becomes the *inclusive test rule* (ITR).

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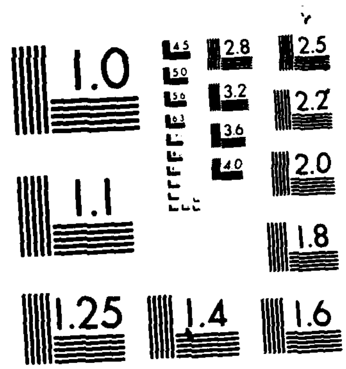


MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

Testing the entire process plan when forming processes are evaluated, requires a *forward reasoning* system because of the changing properties of the material being worked on. Testing of each operation takes into account the deformation encountered in previous operations (strain history) and the route of metal flow in current operation, and not just the initial and final geometries of the workpiece.

8.2 Mechanism of Generating The ITR

8.2.1 AGTR System

The AGTR system is built as a two-layered, deterministic, RBS. The upper layer - ***abstract AGTR*** - is the domain independent formulation, and the bottom layer contains the instantiated knowledge. The abstract AGTR subsystem guides a user to set up the category test files and to encode into each file the appropriate TR's in a predefined structured form. The rules, in the abstract and the application layers, are put in Horn clause form. A schematic AGTR system in Figure 1.

8.2.2 Abstract Formulation of AGTR

The abstract part of the AGTR system is formulated as a hierarchy of four layers of rules, with **Rule 1** being the root. Henceforth, in the abstract formulation, rule number corresponds to the layer and rule components are defined in terms of the designated process planning domain.

Abstract AGTR Rule 1:

ITR: test if an operation can start and be successfully completed:

ITR produces "success" **if**

$$\bigcap_i \{ CTR_i \text{ produces "success" } \}. \qquad \{ i \in \text{Test-Category} \}.$$

The RHS of **Rule 1** reads: "for all categories, each of the category TRs (CTR) produces 'success'". Typical categories: machine power, machine structural requirements, etc.

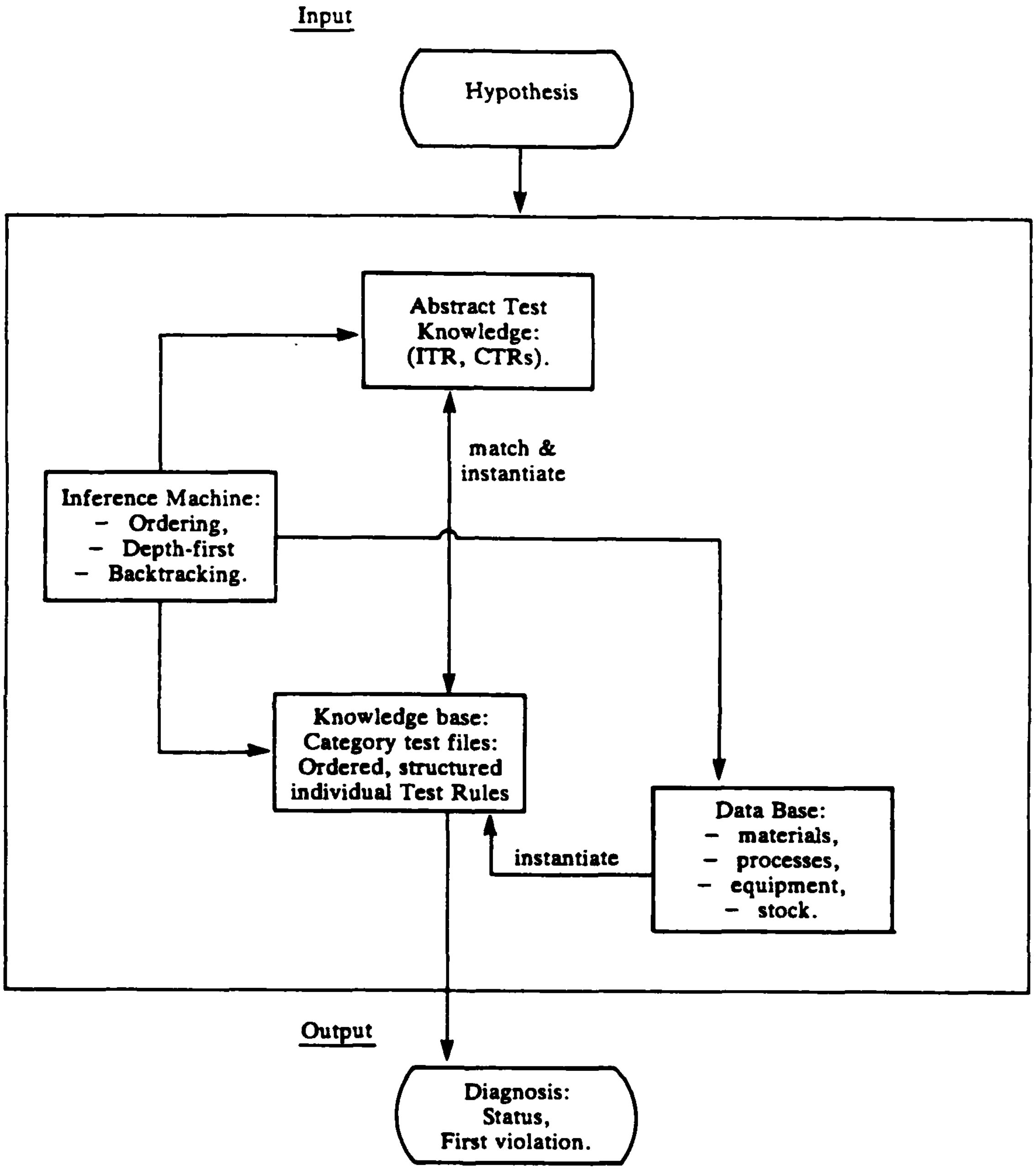


Figure 8-1. AGTR module

Abstract AGTR Rule 2:

CTR_i is tested through the generation of the inclusive test rule for the examined category i:

CTR_i produces "success" **if**

$$\bigcap_j \{TR_{i,j} \neg\text{produces "unsuccess"}\}. \qquad \{ TR_{i,j} \in Test-Category_i \}.$$

The RHS of **Rule 2** is read: "none of the TRs belonging to the "i" category, - $TR_{i,j}$ - produces: 'operation unsuccessful'". For example, in testing a deep-drawing operation, $TR_{i,j}$'s that belong to *machine-power-sufficiency* category check if the required punch and blankholding force can be satisfied.

Thus ITR_i stands for the inclusive TR of category "i". Specific TR's are checked as shown below:

Abstract AGTR Rule 3:

$TR_{i,j}$: determine the effect of a particular TR:

$TR_{i,j}$ $\neg$produces "unsuccess" **if**

$TR_{i,j}$ $\neg$active **or**

$TR_{i,j}$ produces "success".

Read as: "a test is considered to produce 'success' if either the rule is not applicable or else the test produces 'operation successful'"

The two conditions of the level 3 rule are elaborated upon in level 4 rules:

Abstract AGTR Rule 4.1:

Determine if $TR_{i,j}$ is active :

TR_j is active **if**

scope of $TR_{i,j}$ contains { initial and final workpiece, and process }.

In this respect, 'active' is synonymous with relevant, applicable.

Abstract AGTR Rule 4.2:

Determine if TR_j produces "success":

$TR_{i,j}$ produces "success" **if**

Boundary of $T-P_{i,j}$ not violated by

{process, initial WP, final WP, strain-history}.

Read: "a test produces 'success' if the boundary of the test-parameter of the rule is not violated".

8.2.3 Implementation of AGTR in a Rule Based System

The AGTR is implemented as a structured rule-based system. As of now, conflict resolution is done by *ordering*, rules and facts are examined for matching *sequentially* within the working memory and *backtracking* is used to search the state-space graph. The computational efficiency can be improved by employing more robust search techniques and conflict resolution strategies. *Structuredness* has two merits: filling the working memory with relevant data-items only and reducing the diversity of classification rules (of workpiece-shapes and of processes).

Structuredness is implemented using the following mechanisms:

1. TRs and the relevant facts of each category are stored in a separate file. A category file is read into memory when required and is deleted after being manipulated. The penalty for reading and deleting a category file is compensated for by the reduced size of the working memory to be scanned for matching.

2. Facts in a category file are formulated as *relations* of a relational data-base.

3. Validity of every TR is defined within a certain scope, and thus each category test-file is composed of the pairs:
{ scope-of-TR, contents-of-TR }.

4. Both the scope-of-TR and contents-of-TR have a category-dependent structure.

The procedure: *construct_itr_of_category*$_i$*_&_test*, that implements Abstract AGTR Rule 2, shows how structuredness principles are applied as a set of Prolog-like rules.

procedure: *construct_itr_of_category*$_i$*_&_test*(itr_i)

construct_itr$_i$(Rule_parameters, Result$_{last-TR}$) ←
    consult(Category_file$_i$),
    itr_i(Rule_parameters, Result$_{last_TR}$).

itr_i(Rule_parameters, Result$_{TR_j}$) ←
  clause(TR$_j$(Rule_parameters), RHS),
  {
   { *not_active_or_succeed*(TR$_j$, Rule_Parameters, Result$_{TR_j}$),
    retract(Operation_conditions),
    retract((TR$_j$(Rule_parameters ← RHS)),
    itr_i(Rule_parameters, Result$_{next-TR}$) } \/
   Result$_{TR_j}$= ['Violated', Test_parameter$_{TR_j}$]
  }.

Rule_parameters = [Process_conditions, Category_variables, Result],
Operation_conditions = [Process, WP$_I$, WP$_F$, Strain_hist],
Category_variables = [Process_capacity, Test_parameter],
consult(X) = read clause X into working memory,
clause(X, RHS) = identify the RHS of clause X,
retract(X) = delete X from working memory.

In the above rules the contents of the appropriate category file are read into the working memory through the *consult* predicate and their effect on the overall feasibility is checked through the *not_active_or_success* predicate. A positive result leads to the checking of the next TR (through the combination of *retract* and itr$_i$ relators). A virtual "cut-fail" mechanism is introduced: once a clause (TR) can be unified (is applicable) it has to produce "success" or else the itr_i produces "fail".

8.3 Applying AGTR to Testing a Deep-Drawing Operation

An application of the abstract formulation of AGTR to the testing of deep-drawing processes assumes the following instantiations:

1. Test-Categories $\in$ { **machine, yield, defect-develop** }. The **machine** category includes the subcategories: { **machine-yield, machine-defect-prevent** }. **machine-yield** contains TRs about machine capabilities to induce yield. **machine-defect-prevent** contains rules about machine capabilities to prevent defects.
   The rationale behind distinguishing between *machine-category* and a general *category*: the non-machine category contains rules that determine feasibility (of start-of-flow and defect-free completion) regardless of *forces* imparted by the machine (press).

2. Test-Files correspond to categories: machine, yield, defect-develop.

3. "Scope of TR" is the 4-tuple:
   1. process,
   2. material,
   3. workpiece specifications at start of operation,
   4. workpiece specifications at end of operation.

4. TRs of the deep-drawing test categories have the following, category-dependent, structure (in a Prolog-like form):

   i. Machine-Capability test category:

   machine_suitable(Machine$_X$, WP$_I$, WP$_F$, Process, T-P, Result) $\leftarrow$
   1. *compute_parameter*(Process, T-P, WP$_I$, WP$_F$, T-P-value),
   2. *capacity_suffice*(Machine$_X$, T-P-value, Result),
   3. *machine_structure*(Machine$_X$, Process, Result).

   ii. Start-of-Flow test category

   flow_start(WP$_I$, WP$_F$, Process, T-P, Result) $\leftarrow$
   1. *largest_force*(Process, WP$_I$, WP$_F$, Force$_{Max}$),
   2. *machine*(Machine$_X$, Machine_power),
   3. *Machine_power* $>$ Force$_{Max}$.

iii. Defect-Develop test category:

defect_develop(WP_I, WP_F, Strain_hist, Process, T-P, Result) ←
  1. *retrieve_boundary_value_&_type*(WP_I, WP_F, Process,
      T-P, Boundary_Value, Boundary_Type),
  2. *compute_T-P_value*(T-P, WP_I, WP_F, Strain_hist,
      T-P_Value),
  3. T-P = [Boundary_type, Boundary_value],
  4. *compare_T-P_&_boundary*(T-P, T-P_Value, Result).

5. Test parameters (T-P's) of the deep-drawing process that are elaborated upon throughout Chap. 3 include:
   - Ram power sufficiency (to satisfy start of flow),
   - Machine size sufficiency.
   - Blankholder power sufficiency,
   - Proper machine structure (e.g.: number of independent slides).
   - D - draw ratio,
   - RD - redraw ratio,
   - DRR - die radius ratio,
   - FTR - flange to wall-thickness ratio.

   A full list of T-Ps is given in §3.2.7.

ITR for the Deep-Drawing Application

Application of the abstract rules of Chap. 3 to testing the feasibility of deep-drawing operations involves instantiation of *relators* and *variables*. Thus far relators are instantiated manually since only a first order predicate calculus is employed. For example, the "construct ITR_i" rules of Chap. 3 are instantiated to "construct and testing ram power sufficiency" in the following rules (textual meaning of the relators and variables is derived from the abstract procedure in §8.2.2):

Test Category: Machine Yield, Power Sufficiency.

T-P: Ram Power

construct_ram_power_test(Rule_parameters, $\text{Result}_{\text{last-TR}}$) $\leftarrow$

consult(Machine_power_test_file),

test_ram_power_sufficiency(Rule_parameters, $\text{Result}_{\text{last-TR}}$).

test_ram_power_sufficiency(Rule_parameters, $\text{Result}_{\text{TR}_j}$) $\leftarrow$

clause(test—ram_power$_j$(Rule_parameters), RHS),

{

not_active_or_succeed(TR_j, Rule_parameters, $\text{Result}_{\text{ram\_power-TR}_j}$),

retract((*scope$_{rule_j}$*($\text{scope}_{\text{Process}}$, $\text{scope}_{\text{WP}_I}$, $\text{scope}_{\text{WP}_F}$))),

retract((*test—ram_power$_j$*(Rule_parameters :- RHS)),

test_ram_power_sufficiency(Rule_parameters, $\text{Result}_{\text{next-ram\_power\_TR}}$)

} \/ $\text{Result}_{\text{test-ram\_power}_j}$= ['Violated', 'Ram Power'].

Structured Test-Rules

The TR of Chap. 3 are formulated in a category-dependent structured form. The following rules illustrate the instantiation of TR and the corresponding computation rules.

T Rule 38 and **C Rule 87.**

scope([deep-drawing, one-stage], ['Blank', 'high quality drawing steel'],
T-P: drawing-force, F.

compute_draw_force([draw, any], 'Force', WP_I, WP_F, F-Value) ←
retrieve_tensile_strength(WP_I, S_u),
retrieve_LD(WP_I, LD),
compute_actual_D(WP_I, WP_F, Actual_D),
compute_cup_wall-thickness(WP_F, t),
compute_cup_circumference(WP_F, L),
K_1 is $1.2\times\frac{\text{Actual\_D} - 1}{\text{LD} - 1}$,
$\lceil$F−Value$\rceil$ is $K_1 \times S_u \times L \times t$.

T Rule 41 and **C Rule 99.**
("bh" or "BH" denotes blankhold force, "P" or "F" ram force):

scope([deep-drawing, one-stage], 'Blank', 'Straight Cup').
T-P: bh-force.
compute_bh([draw, any], 'BH', WP_I, WP_F, BH-Value) :-
compute_draw_force([draw, _], 'F', WP_I, WP_F, F-value),
{ { Material_{WP} = {'Stainless Steel' \/ 'Brass'}, K is 2 } \/
K is 1 },
compute_relative_wall-thickness(WP_F, Relative_t),
compute_relative_punch_profile(WP_F, Relative_P_profile),
compute_relative_die_profile(WP_F, Relative_die_profile),
compute_actual_D(WP_I, WP_F, Actual_D),
retrieve_bh_ratio_to_punch(Relative_t, Relative_punch_profile,
Relative_die_profile, Actual_D, BH_to_F_Ratio),
BH-Value is K × BH_to_F_Ratio × F−Value.

The AGTR can be viewed as an independent module. It formalizes a solution to the automatic generation of the inclusive TR to test a hypothesis within a "Hypothesize & Test" procedure. It stipulates certain properties of the test knowledge. These require the test knowledge to be composed of practically independent TR that are valid within a certain scope of process parameters and workpiece features. The abstract formulation provides the

supervisory control procedures and a framework for encoding the specific knowledge. The reasoning program manipulates the working memory to contain relevant test files and candidate TRs only. In APP, these TRs are activated if their scope contains both the process and workpiece features.

8.4 Example

The following example, based on the technological KB of Chap. 3, illustrates the idea of the automatic construction of the ITR. The example deals with constructing the ITR the operation should satisfy, but does not proceed to perform the test itself. Notwithstanding that, one must remember that in actual operation allocation of an individual TR is immediately followed by executing the test, before looking for the next individual TR. Problem input consists of the initial and final workpiece specifications (Fig. 2, *a* and *b*) and the mapping operation: **cupping.** The sample KB is chosen to be the following 9 pairs of rules. For ease of illustration these pairs are named by consecutive numbers and arranged so that the T Rule is listed before the corresponding C Rule.

#1: {38,87}, #2: {38,89}, #3: {41,99}, #4: {44,104}, #5: {50,123}, #6: {45,115}, #7: {45,105}, #8: {47,112}, #9: {47,120}.

The RHS of the CTR is composed of the predicates: $CTR_{machine-yield}$, $CTR_{machine-defect-prevent}$, CTR_{yield}, $CTR_{defect-develop}$. Activation is determined through the *scope_contain* predicate.

The **machine-yield** test file includes pairs #1 and #2.

scope_contain($Pair_1$, Process, WP_I, WP_F) $\leftarrow$

recognize_main_shape(WP_I, $Main\_Shape_{WP_I}$),

recognize_main_shape(WP_F, $Main\_Shape_{WP_F}$),

Process = [deep-drawing, one-stage],

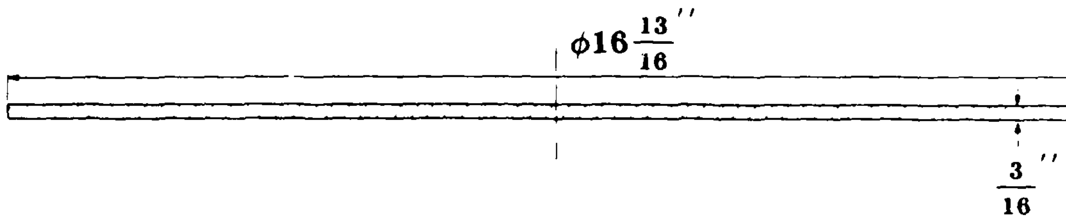
$Main\_Shape_{WP_I}$ = ['blank', 'equal *t*'],

$WP_{material}$ = 'high quality drawing steel',

$Main\_Shape_{WP_F}$ = ['straight walled cup', 'equal *t*'].

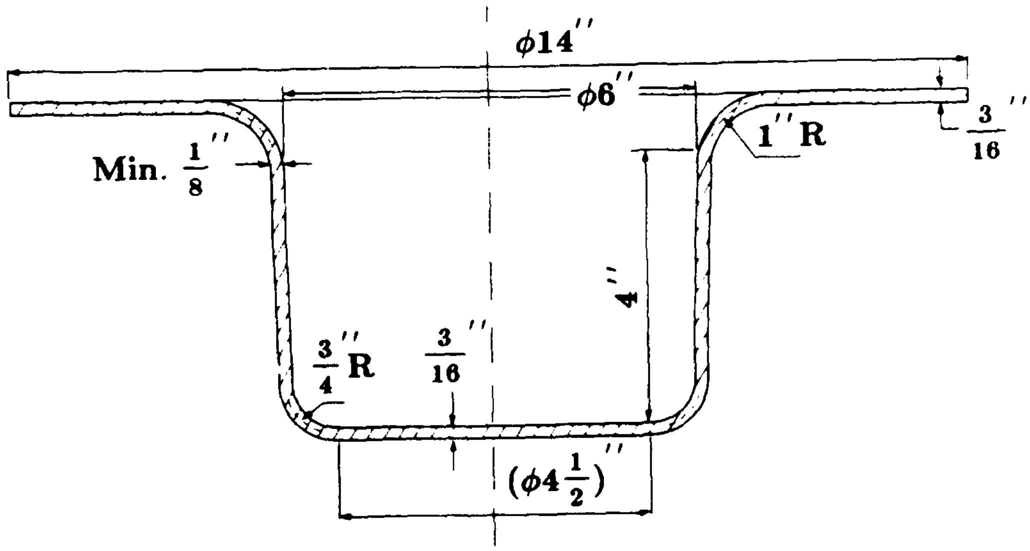
Intermediate instantiations include:

- $Main\_Shape_{WP_I}$ = ['blank', 'equal *t*'],
- $Main\_Shape_{WP_F}$ = ['straight walled cup', 'equal *t*'],



Material of the sample problem is a high quality drawing steel of 220 Brinell hardness.

a. Workpiece at start of operation



b. Workpiece at end of operation

Figure 8-2. Initial and final workpiece

and the final answer: **Yes** (pair #1 is active).

In a similar manner pair #2 is found to be inactive (material does not match). The **machine-defect-prevent** test file includes TR #3. Since pair #3 is inactive (relative thickness of the workpiece outside the scope of the rule), the $ITR_{machine-defect-prevent}$ is true independently of workpiece features and process parameters. Pairs #4 to #9 belong to the **defect-test category**. Only pair #7 is active. There is no sample rule belonging to the **yield** category in the sample knowledge base. Thus the **ITR** becomes:

itr('Cupping', WP_I, WP_F, Strain_hist, Result) $\leftarrow$
    $Machine_X \in$ plant-equipment,
    machine_yield($Machine_X$, 'Cupping', WP_I, WP_F, Result),
    { *defect_prevent*('Cupping', WP_I, WP_F, Strain_hist, Result) $\vee$
     Result = ['Rectifiable', Defect-develop-T-P] }.

Where:

machine_yield($Machine_X$, 'Cupping', WP_I, WP_F, Result) $\leftarrow$
    suffice_draw_force([drawing, Any], WP_I, WP_F, Result).   (pair #1).

defect-prevent('Cupping', WP_I, WP_F, Strain_hist, Result) $\leftarrow$
    contain_draw_ratio('Cupping', WP_I, WP_F, Strain_hist, Result).
                                                                (pair #7).

9. AGMPO EXAMPLES

9.1 Modes of Running AGMPO

The AGMPO system can be operated in several modes. It can generate process outlines for a given "machined" part, fulfilling its designated task, as well as operate each of its major subsystems independently. The ACDP subsystem can automatically design a deep-drawable preform out of which the required part can be machined. The AGFPO module can assess the deep-drawability and generate a deep-drawing process outline for a deep-drawable workpiece. The ACDP manipulates the shape only. It accepts a CAD representation of the part, i.e. a set of points representing the polygonal cross section. The input to the AGFPO subsystem is a CAM representation of a generalized cup. The performance of each of these modes is illustrated by an example, in the following sections. The first example describes significant stages in obtaining automatically a deep-drawable circumscribing preform. The second example gives the details of a stand-alone deep-drawing process planning activity. The third example shows the automatic generation for a multi-technology process outline for the given part, which puts the two subsystems together.

9.2 Example I: Automatic Design of the Circumscribing Preform

The following example, taken from an ACDP run, illustrates a simple application of G&TR in the design of deep-drawn circumscribing preform. It succeeds with the first hypothesis and tens of rectification attempts, three of them displayed here. For simplicity of substantiation it is assumed in this example that the only design requirements the cup has to meet are:

- full containment of the final workpiece,
- nominal wall-thickness is selected from available stock, and

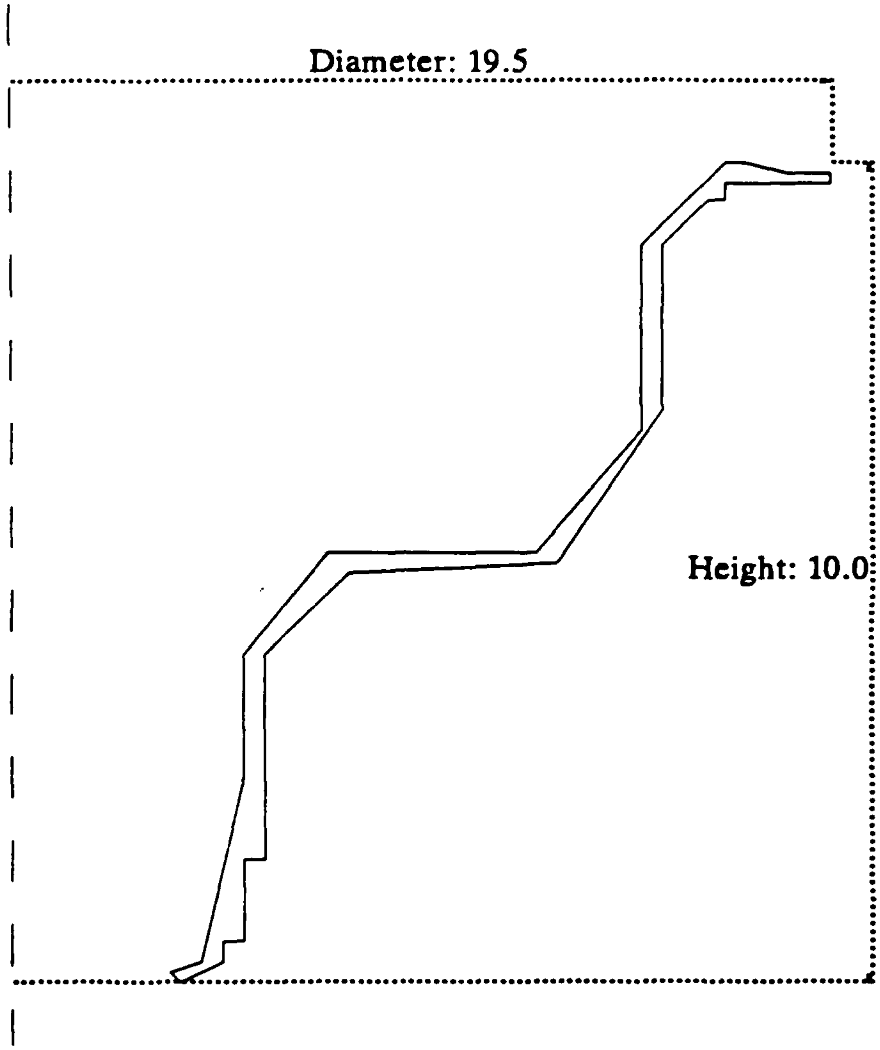
— the circumscribing cup will reasonably approximate the minimum possible wall thickness and optimum recess-radii ratios, in this order.

A recess-radius ratio is the ratio between the recess radius and the nominal wall-thickness. Tentative, but largely practical values are employed. The lower bound values for both "die-shaped" and "punch-shaped" recess-radii ratios are 2 and the optimum values for both are taken to be 5. As noted in Chap. 3 the optimum recess-radii ratio values are in the vicinity of 10, but the contribution to the enhancement of drawing features between 5 and 10 is not as significant as in the smaller range. The input is the CAD representation of the geometry of the required finished part, "part_a". Its cross section is plotted in Fig. 1*a* and the representation is given in Fig. 1*b*.

The program starts by verifying geometry constraints. Geometry constraints here stipulate that the part be axisymmetric and monotonic. The verification succeeds, implying that the part features allow it to be machined from a deep-drawable preform.

The hypothesis stage is designated to generate the initial cup that will be checked for circumscription of part_a, or, if a cup cannot be produced, - the *skeleton* on which the cup will be later generated. The rules for generating the initial hypothesis start with selecting the wall the circumscribing preform will strive to track. In part_a, the number of vertices of the inner wall is smaller than that of the external wall and therefore the inner wall is selected as the reference wall. Next, the maximum wall thickness, w.r.t. the wall of reference, is determined. The maximum wall thickness in part_a is found to be: 0.460977. The uniform wall-thickness circumscribing polygon is drawn in Fig. 2. The *medial* is found from the uniform wall-thickness circumscribing polygon and is shown in Fig. 3.

From now on, and until either a circumscribing cup is generated or the hypothesis and subsequent rectifications fail, the circumscribing polygon is put aside and only the medial is manipulated. The hypothesis stage proceeds with the determination of the minimum wall thickness of the circumscribing polygon. The proper minimum wall thickness, found by searching the data base of the available stock, is 0.5. The initial hypothesis attempts to produce a cup of uniform wall thickness of 0.5 with optimal recess radii. If the initial medial can be *directly* smoothed using the optimum recess radii and initial



a. part_a: cross section.

[
[2,0],[2.5,0.25],[2.5,0.5],[2.75,0.5],[2.75,1.5],
[3,1.5], [3,4], [4,5],[6.5,5.125],[7.75,7],[7.75,9],
[8.5,9.75],[9.75,9.75], [9.75,9.875],[9.25,9.875],
[8.75,10],[8.5,10],[7.5,9],[7.5,6.75], [6.25,5.25],
[3.75,5.25],[2.75,4],[2.75,2.5],[2.25,0.25],[1.875,0.125]
]

b. CAD representation of part_a.

Figure 9-1. part_a: plot and representation

wall-thickness parameters then the hypothesis produces a cup. Otherwise the initial medial is the output of the hypothesis. It serves as a basis for later changes. The optimum smoothing rules smooth each vertex using the largest possible recess radii. It attempts to suit to each vertex the best recess radius allowed, as determined by the wall thickness. In this case, smoothing the initial medial with optimum recess radii and minimum wall thickness succeeds. The resultant cup is drawn, together with part_a, in Fig. 4.

Since the initially hypothesized cup does not fully circumscribe the part - intersection of the cross sections is detected - rectification rules are invoked to modify the initial medial w.r.t. varying wall thicknesses, to try to obtain a circumscribing cup. The first rectification set of rules that is fired is the "erase intermediate vertices". It fails in the end, - too thick a cup is produced - and is not displayed here. The "discard exceedingly small segments of the medial" set of rectification rules is then invoked. These rectification variations start too with smoothing the modified medial under the optimum recess radii rules. A series of these generations fails to contain the part. The last in this series is shown in Fig. 5. It matches the maximum possible wall thickness of 0.6875 of the data base. The optimum recess radii rule exhausts its possibilities when an optimum recess radius forces the value of the adjacent element to be of zero length. Once rectification with optimum recess radii fails, rectification with minimum recess radii is invoked. The initial minimum recess radii cup is shown in Fig. 6. It intersects the part. Successive attempts to increase the wall thicknesses to values present in the available stock, follow. Rectification succeeds with wall thickness of 1, and the circumscribing cup is shown in Fig. 7. An overall view of the circumscription is demonstrated in Fig. 8.

Eventually, changes in wall-thickness that will be brought about by the deep drawing deformations have to be taken into account in the design of the preform. The synthesis of the feedback from the manufacturing module that derives these changes is not dealt with in this thesis.

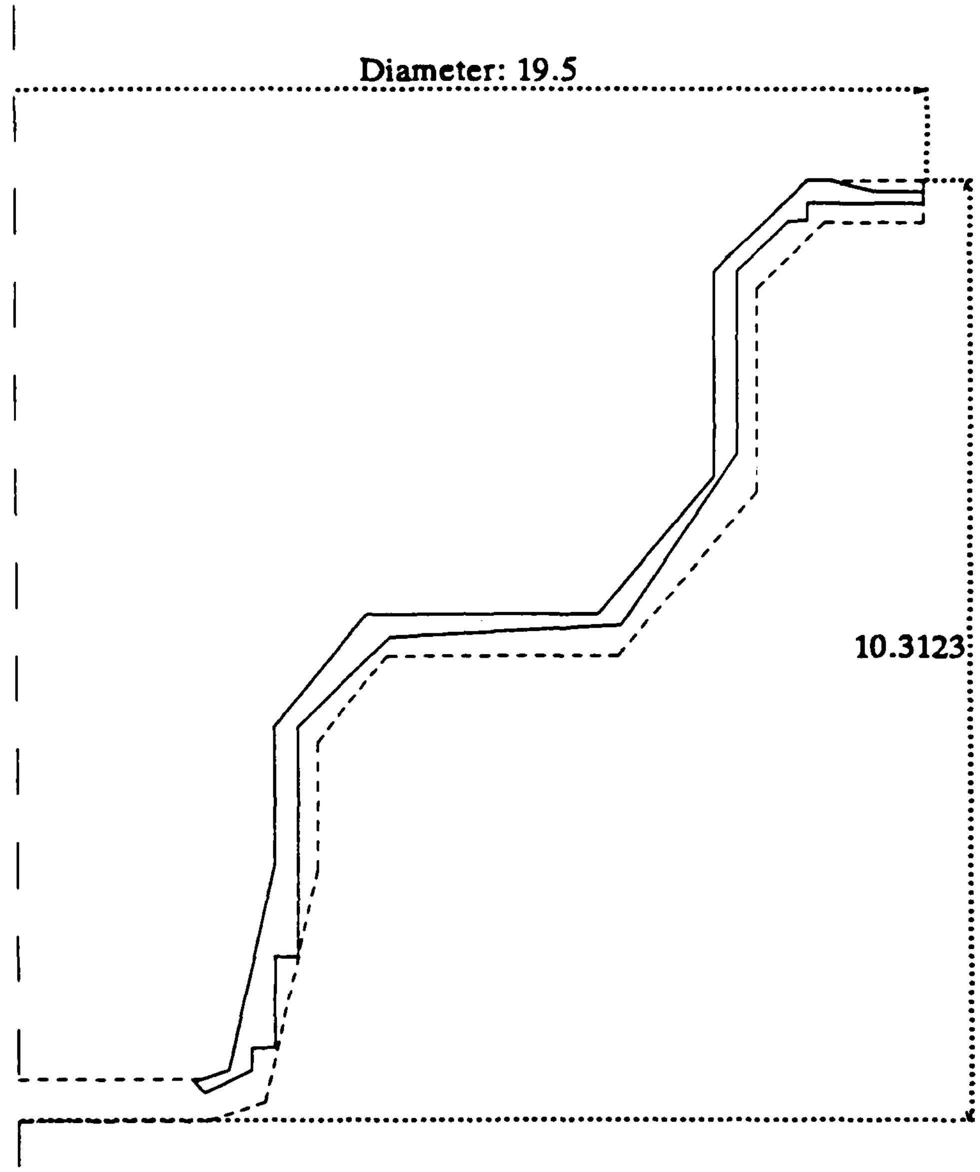


Figure 9-2. part_a and its uniform wall-thickness circumscribing polygon.

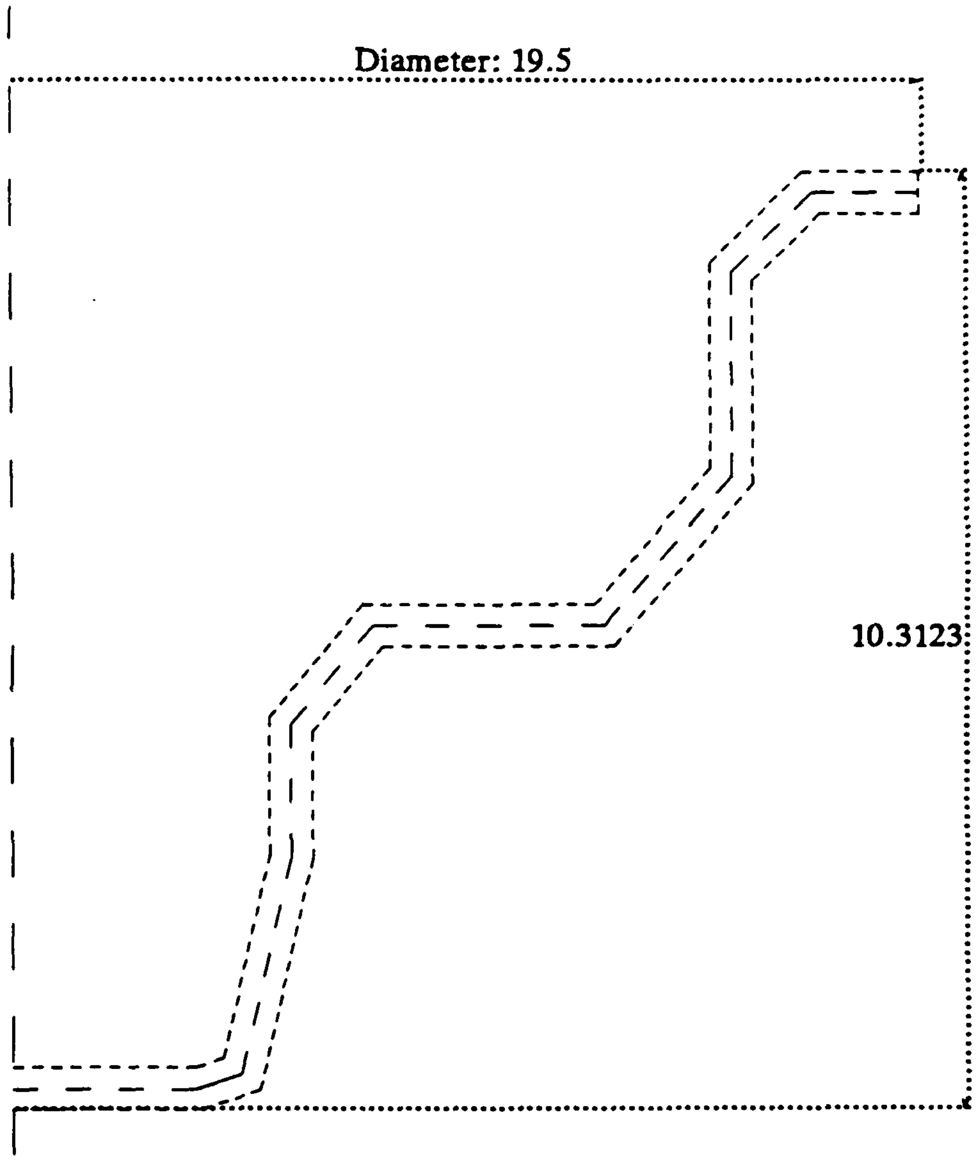


Figure 9-3. Uniform wall-thickness polygon and its medial.

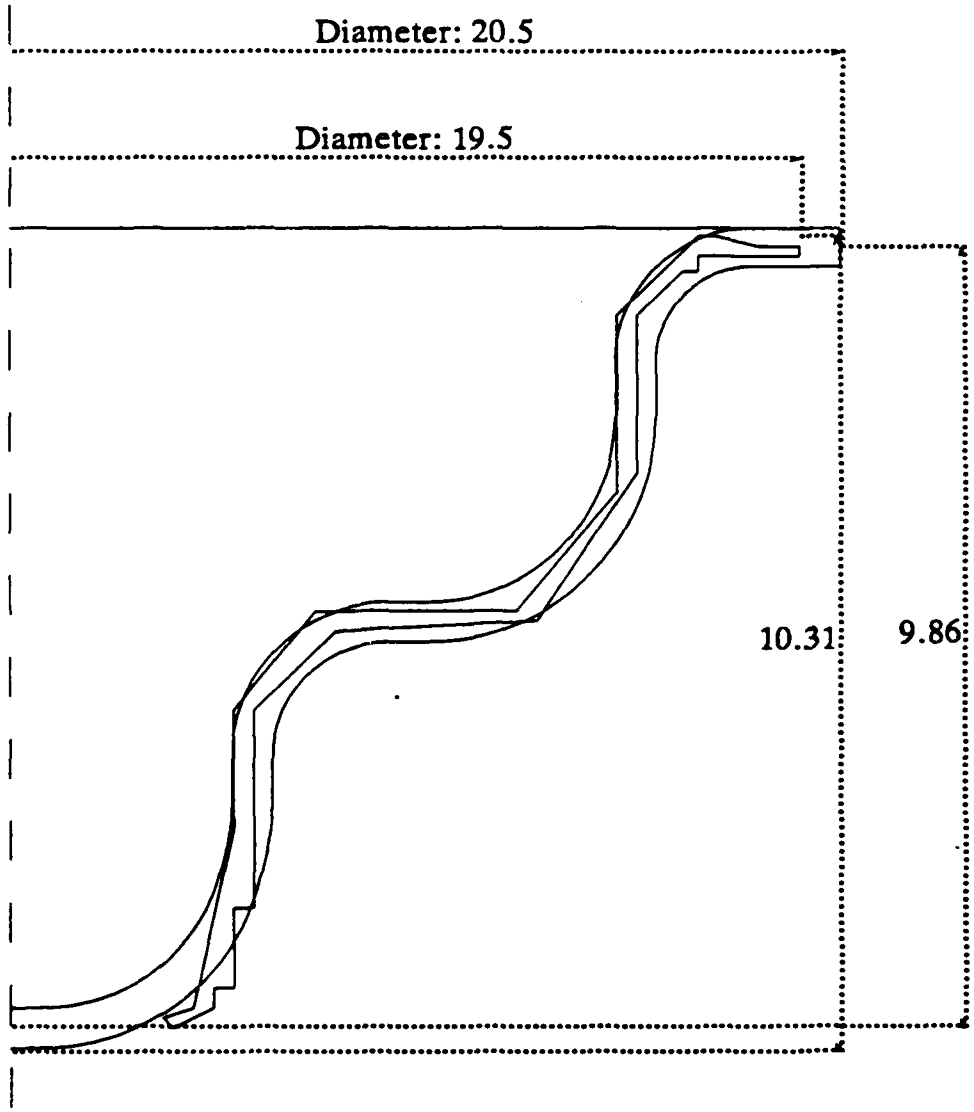


Figure 9-4. Initially hypothesized cup, of optimum recess radii and minimum wall thickness, intersecting part_a

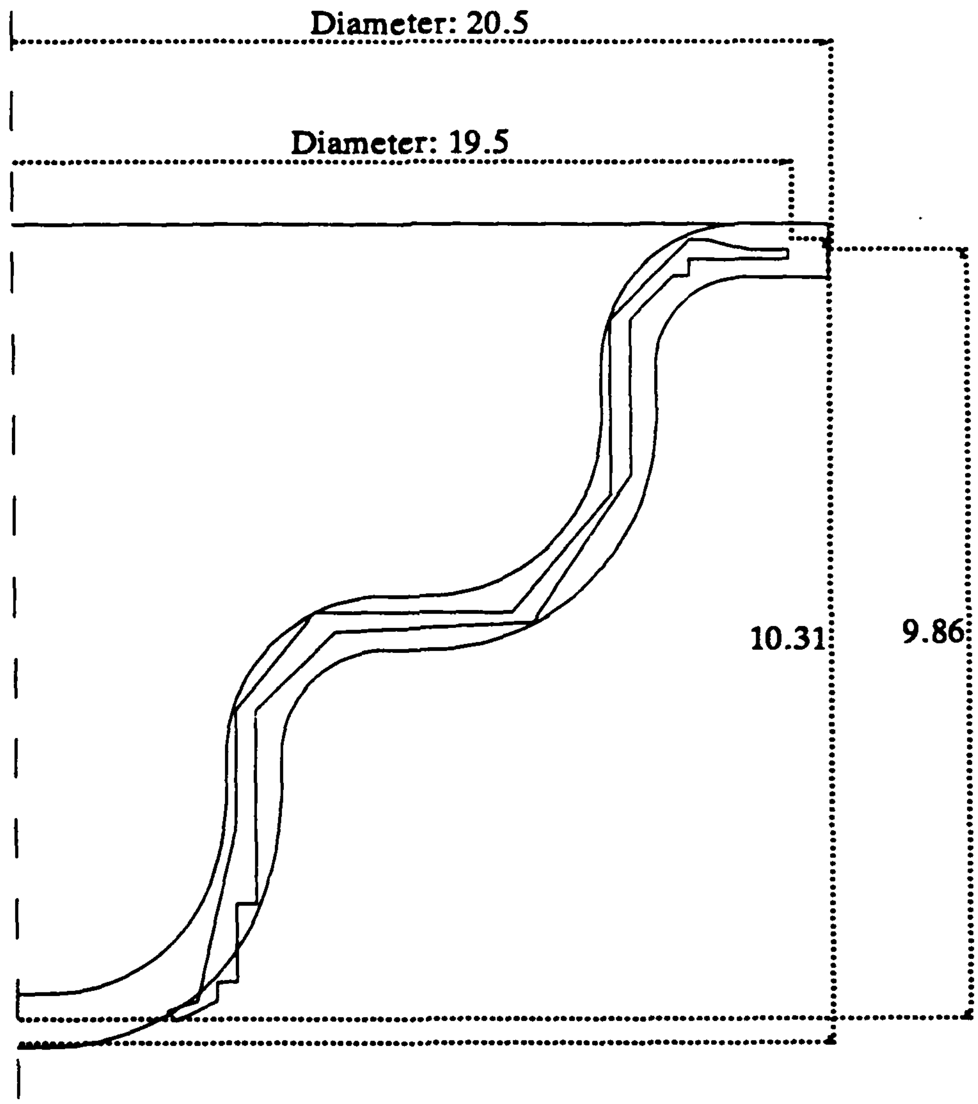


Figure 9-5. Rectified cup: optimum recess radii and maximum wall-thickness: 0.6875, intersecting part_a

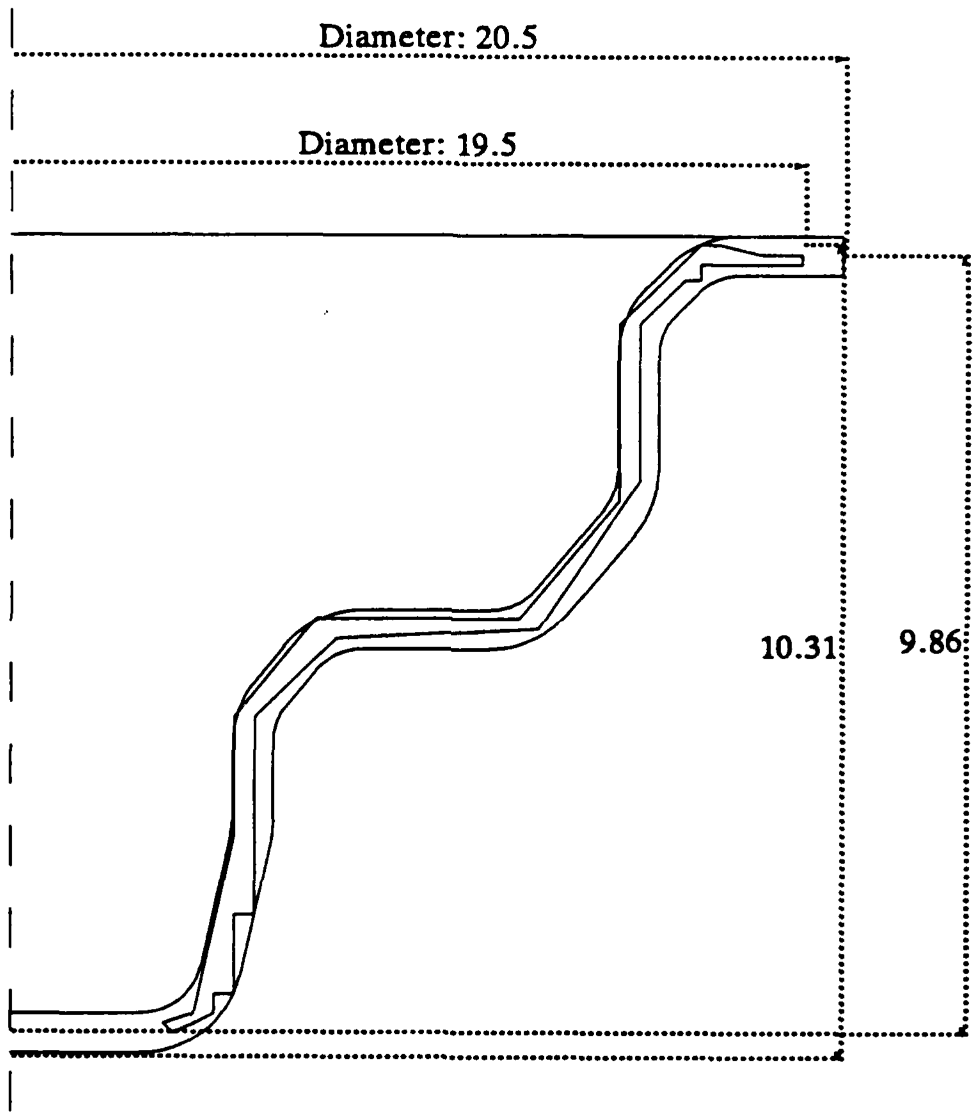


Figure 9-6. Rectified cup: minimum recess radii and minimum wall-thickness 0.5, intersecting part_a

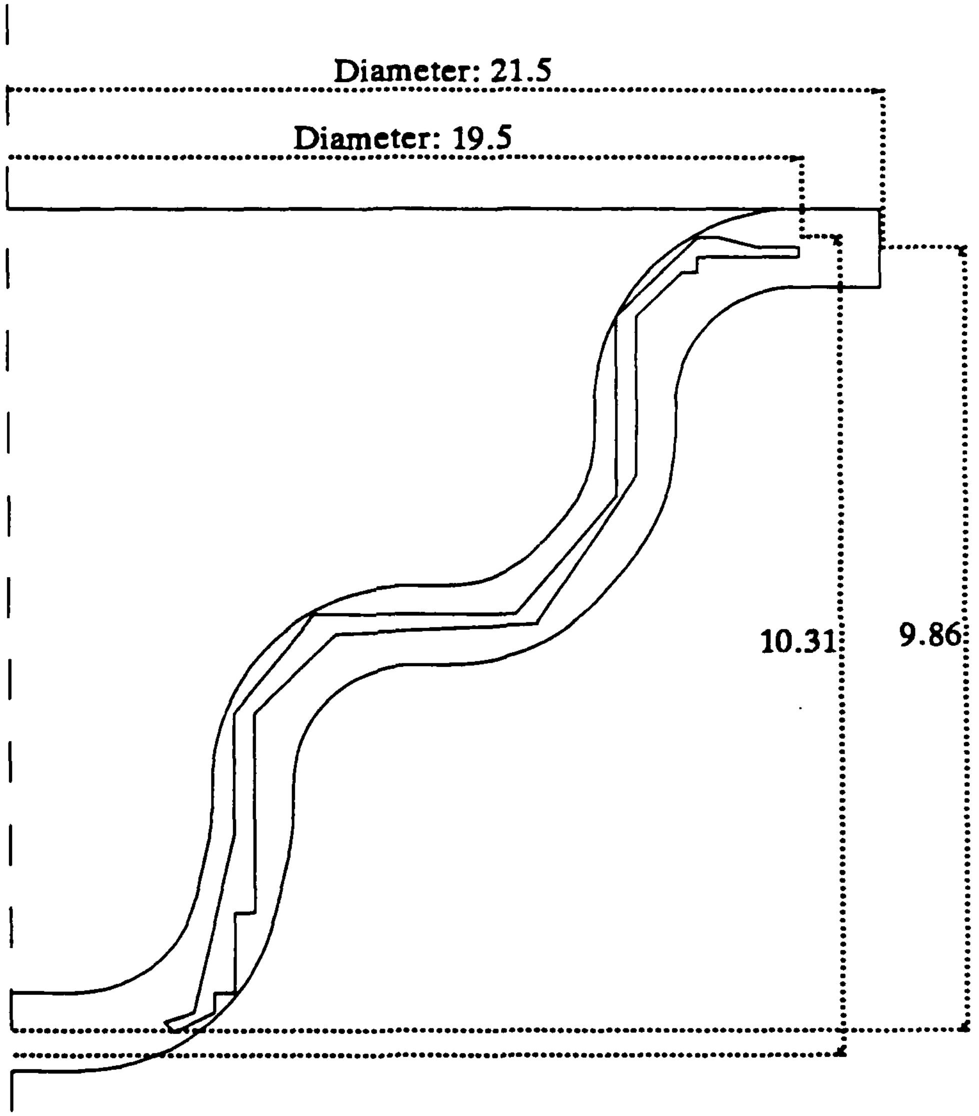


Figure 9-7. Rectified cup: minimum recess radii and maximum wall-thickness: 1.0, circumscribing part_a

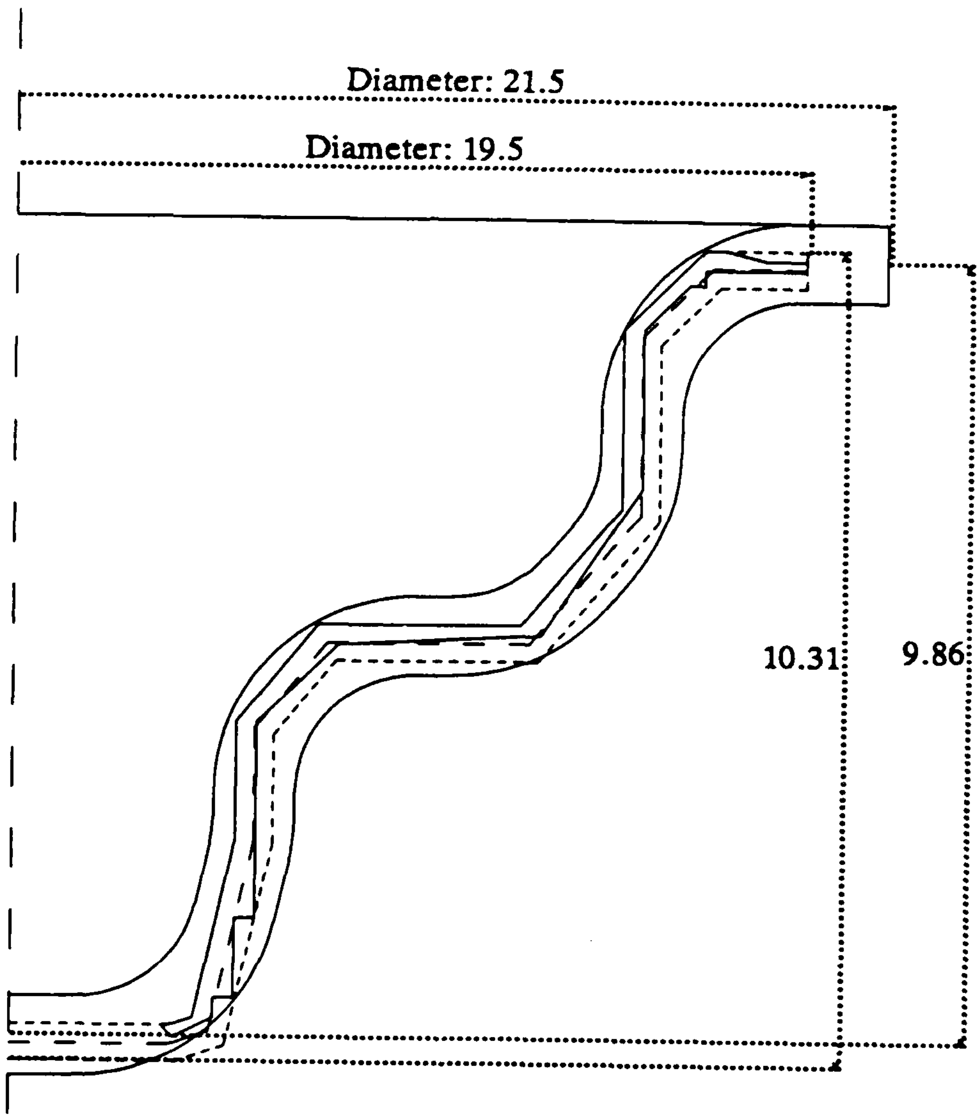


Figure 9-8. Circumscription overview: circumscribing cup, part_a, uniform wall thickness circumscribing polygon and medial

Performance and Computational Aspects

The ACDP system is written in Prolog and runs on the UNIX system at Purdue University. A question of the form: "what is the circumscribing deep-drawn-type preform that contains part_X" invokes the circumscribing design program. Technological design rules are taken from the deep-drawing domain of expertise (Chap. 3). Rules regarding recess radii are interpreted in the following manner:

- "**if** a recess has to be introduced **then** it has to be within the particular allowed range.".
- "**if** a recess has to be introduced **then** it is going assume the optimal value or the best possible value if optimum is not within allowed range.".

Employing *backtracking* and close control of the search through the *cut-fail* mechanism, typical search-spaces are within the 60,000 to 120,000 nodes range for circumscribing a 25-surfaces part. Because of the size of the search, global stack-size limits are frequently encountered and manual modifications have to be employed in order to prune the search, and to bring the system to focus on the more promising rectification rules.

9.3 Example II: Generation of A Deep-Drawing Process Outline

The following example utilizes the AGFPO subsystem to automatically generate the process outline to deep-draw a thin, composite cup. Given the required cup as shown and represented in Fig. 9, the AGFPO module creates automatically the initial hypothesis by manipulating the D Rules and the corresponding C Rules. The final cup is manipulated backwards. With each geometry, the previous cup it was drawn from is hypothesized until a blank disc is reached. The resulting hypothesized process outline is shown in Fig. 10.

Once an initial hypothesis is available, *test_and_rectify* is invoked. This step is exemplified here by Operation #3. Operation #3 is initially assumed to be direct redrawing. A window of the initial and final geometries of operation #3 along with the material and the strain history is given in Fig. 11. The rectification knowledge base is built of the rules elaborated upon in Chap.8. Rectification rules utilized in the AGFPO subsystem essentially reduce the severity of strains by introducing intermediate stages. These are R Rules: **57**, **63**, **64** and **65**. Since LD (Limit Draw ratio) was violated, the rectification rules that take care of reducing severity of strains are invoked. The outcome is schematically described in Fig. 12. It is shown there that two intermediate passes have been inserted between the initial and final states.

The rest of the initially hypothesized operations were tested along these lines and rectified if needed. It was found that the initially hypothesized operation #4 needed to be rectified too. That was satisfied by incorporating one additional intermediate pass. The final outcome is schematically described in Fig. 13. For clarity of demonstration the geometries derived from the initial hypothesis are displayed in the right column and the rectified passes are displayed in the left column.

Performance and Computational Aspects of AGFPO

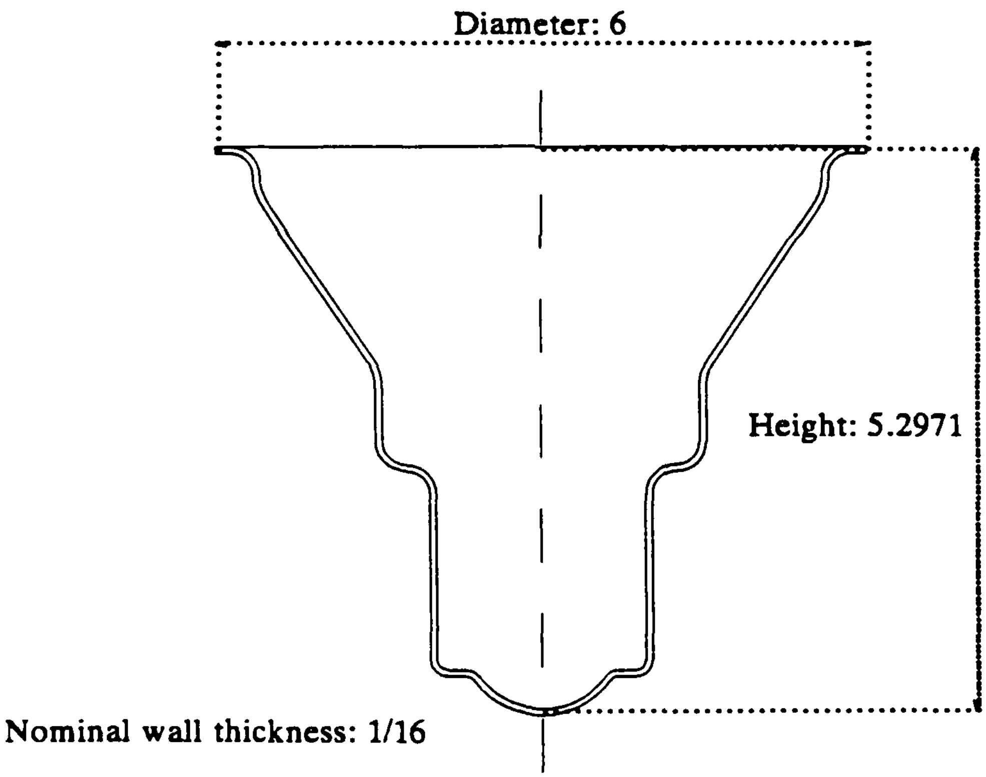
The AGFPO subsystem is written in Prolog and runs on the UNIX operating system. The user feeds in a "question" specifying the final required cup. Then the system, free of user intervention, generates a deep-drawing process outline and plots the sequence of cups. About 40 of the technological rules formulated in Chap. 3 are already programmed. The system

satisfactorily generates process outlines that can be contained within the search-spaces of the $\simeq$100,000 nodes range. This search space corresponds to drawing composite cups of up to ten elements, the first hypothesis and subsequent rectifications succeed, and first-degree-only rectifications are employed. For this scope about one tenth of the search space is devoted to the generation of the initial hypothesis. Because of system constraints - global stack-size limits - larger programs have to be split or else the plotting facilities not employed. By a rough estimate, programming the entire scope of rules may engender three times that number of nodes for *each* additional hypothesis created.

At this stage, the AGFPO subsystem can generate fairly good deep drawing process outlines for composite cups with straight and tapered elements. It is not fully debugged for hemispherical elements. Process outlines produced by the system were compared with solutions to composite stampings in [Jones]. Many of them proved surprisingly similar.

```
[
 6,
 [ e1, h, 1/16, [23/4], 1/4 ],
 [ e2, v, 1/16, [0], 1/2 ],
 [ e3, a1, 1/16, [0.584894, 1.44789], 1/2 ],
 [ e4, v, 1/16, [1/2], 1/4 ],
 [ e5, h, 1/16, [9/4], 1/4 ],
 [ e6, v, 1/16, [25/16], 1/8 ],
 [ e7, h, 1/16, [1.0], 1/8 ],
 [ e8, r1, 1/16, [3/4, 0.5], 0 ]
].
```

a. Coded representation of cup_b



b. cup_b plot

Figure 9-9. Coded representation of cup (a) and its plot (b). (Material: Austenitic stainless steel)

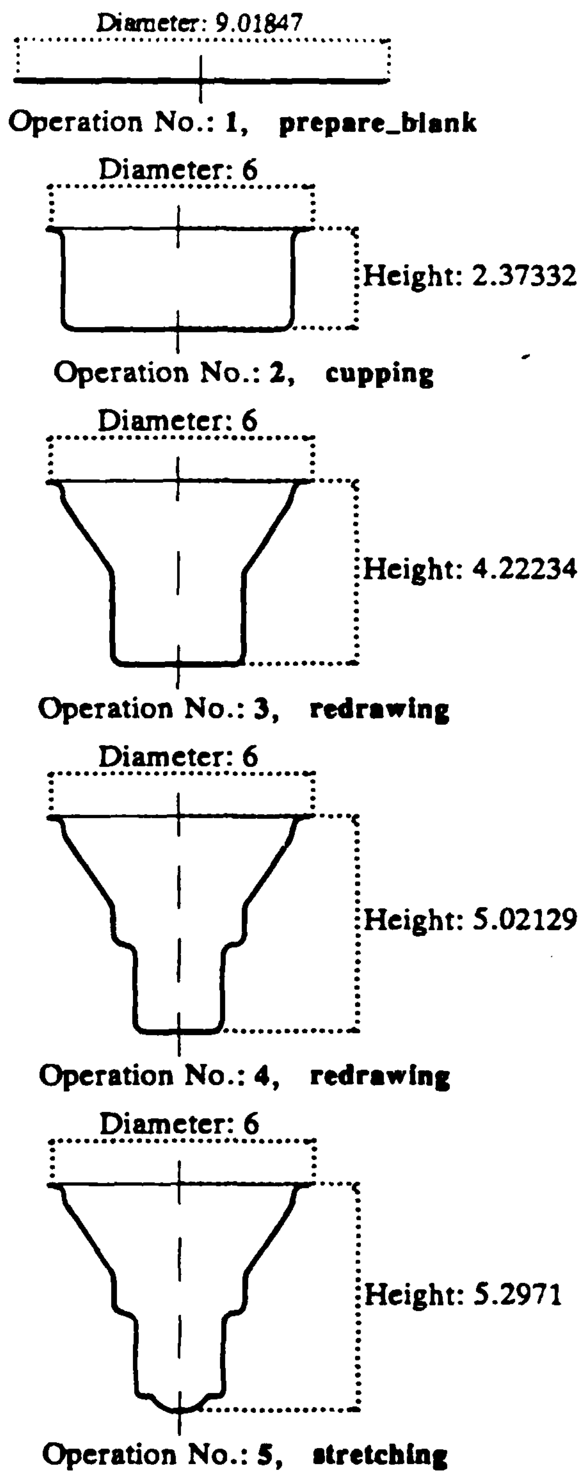
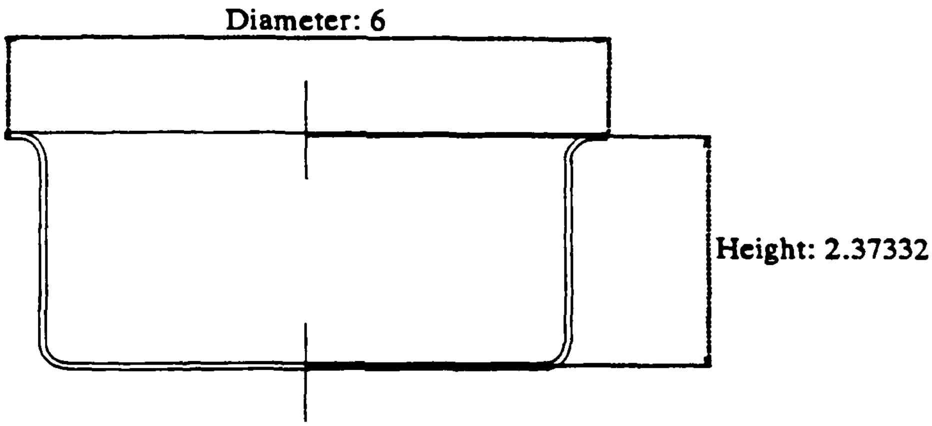
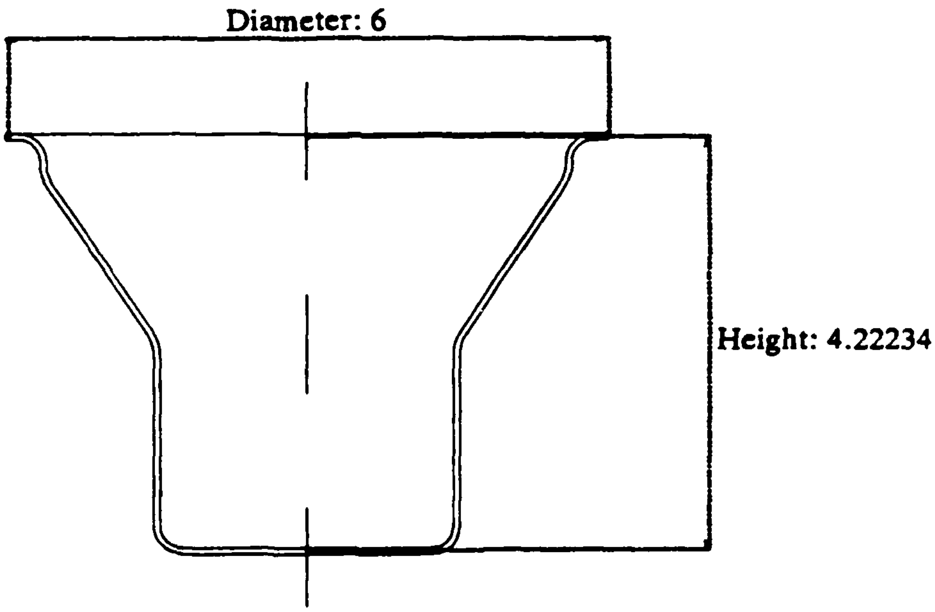


Figure 9-10. The initial, hypothesized, untested process-outline



Strain history: drawing ration: 1.7.

Operation No.: 2, initial geometry after cupping.



Operation No.: 3, initial hypothesis: redrawing.

Material: High quality deep-drawing stainless steel.

Strain history: Initial cupping imparted a 1.7 drawing ratio.

Figure 9-11. Initial and final specifications of hypothesized operation #3.

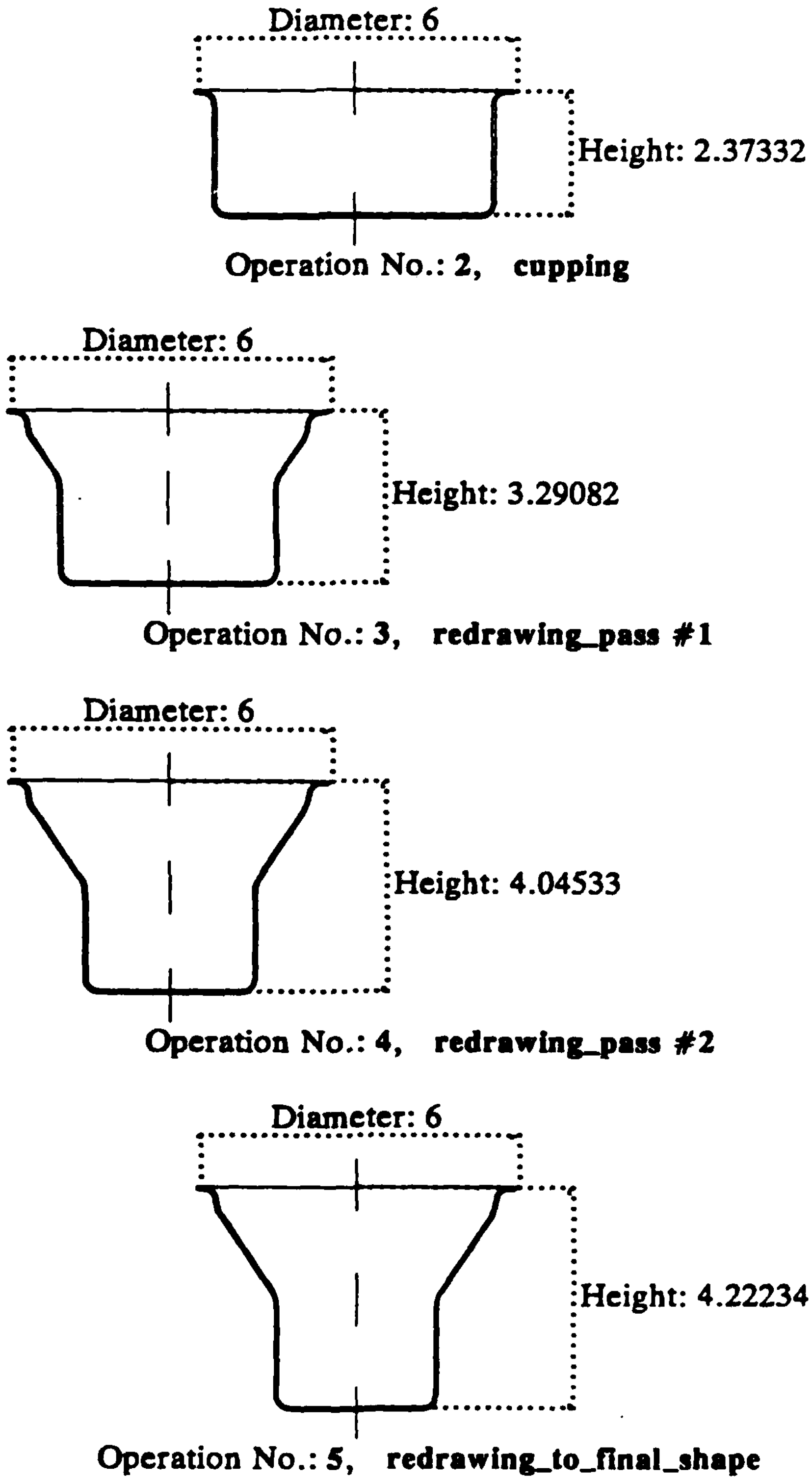


Figure 9-12. Operation #3 rectified locally

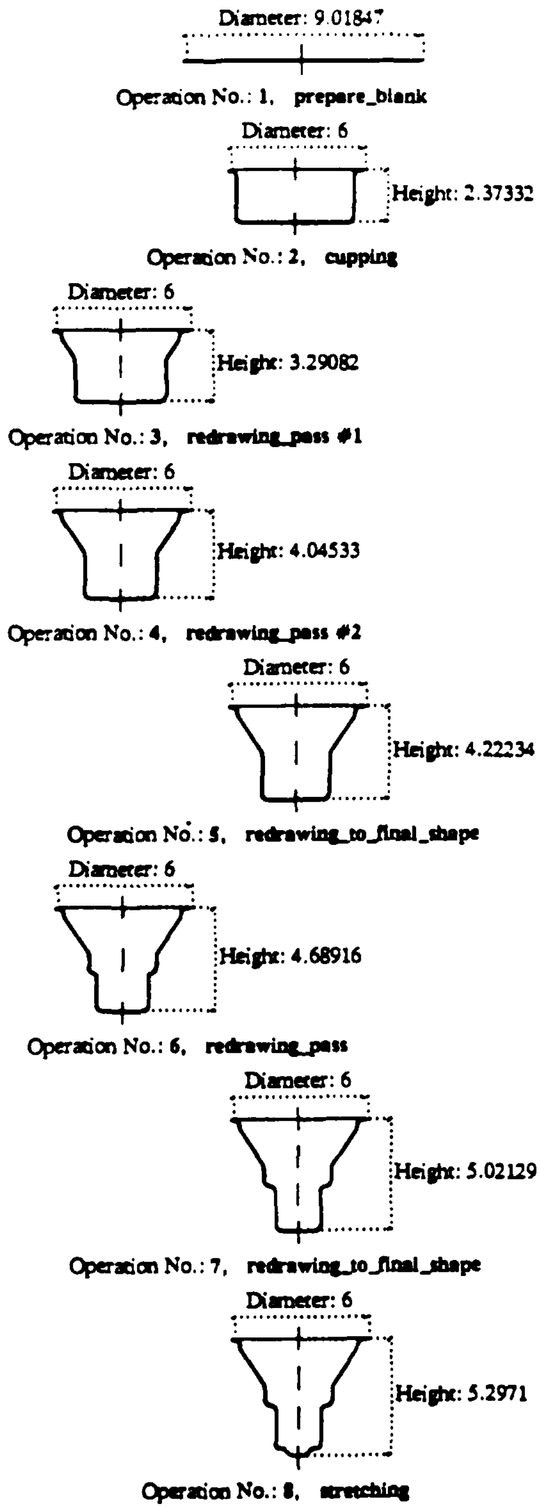


Figure 9-13. Incorporation of local rectifications into a rectified process outline

9.4 Example III: Multi-Technology Process Outline Generation

The following example illustrates the integrated AGMPO system. The input is read by the ACDP module and the circumscribing cup produced by that system is the input to the AGFPO module, which creates a process outline to manufacture it. It is presumed that the material added during the automatic circumscription is removed by rotational machining processes. mainly turning and grinding.

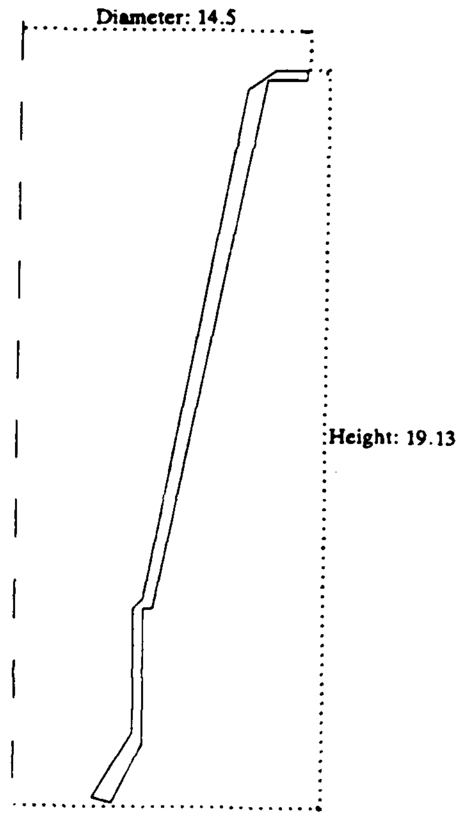
The CAD representation of the geometry of the required finished part, "part_c", and the rest of its specifications are shown in Fig. 14*a* and Fig 14*b*. The integrated generation starts with the design of the preform. The cup that satisfies the design specifications is designed with minimum die recess radius of 1.4 times the wall thickness, for relative wall thickness larger than 0.025. The initial circumscribing polygon is of 0.493387 wall thickness. The overall circumscription is plotted in Fig. 15. It should be noted here that recess radii smaller than twice the wall thickness are acceptable by the process outline producing system, though it would not generate such radii for *intermediate* passes. The AGFPO subsystem is activated with the resultant cup.

The initial process outline is generated as shown in Fig. 16. Testing and rectification of this process outline introduces one intermediate cupping pass, for operation #2. That pass rectifies both the larger than allowed in one pass reduction and the 'sharp' recess radius of the die. The final deep drawing process outline is shown in Fig. 17 and the multi-technology process outline is in Fig. 18.

The AGMPO system searched about 80,000 nodes for the generation of this simple part. More composite parts and process outlines run into global stack limits with the current system, as observed with the runs of the ACDP and AGFPO subsystems.

```
part_data(
    part_c,
    'Austenitic stainless steel',
     [
      [2.5,0],[3.25,1.5],[3.25,5],[3.5,5],[6.25,18.75],
      [7.25,18.75],[7.25,19],[6.45,19],[5.75,18.5],[3.25,5.25],
      [3,5],[3,1.8],[2,0.125]
     ],
     [ 10, 400 ]
      ).
```

a. part_c, CAD representation.



b. part_c: cross section.

Figure 9-14. part_c: CAD representation and plot of cross section

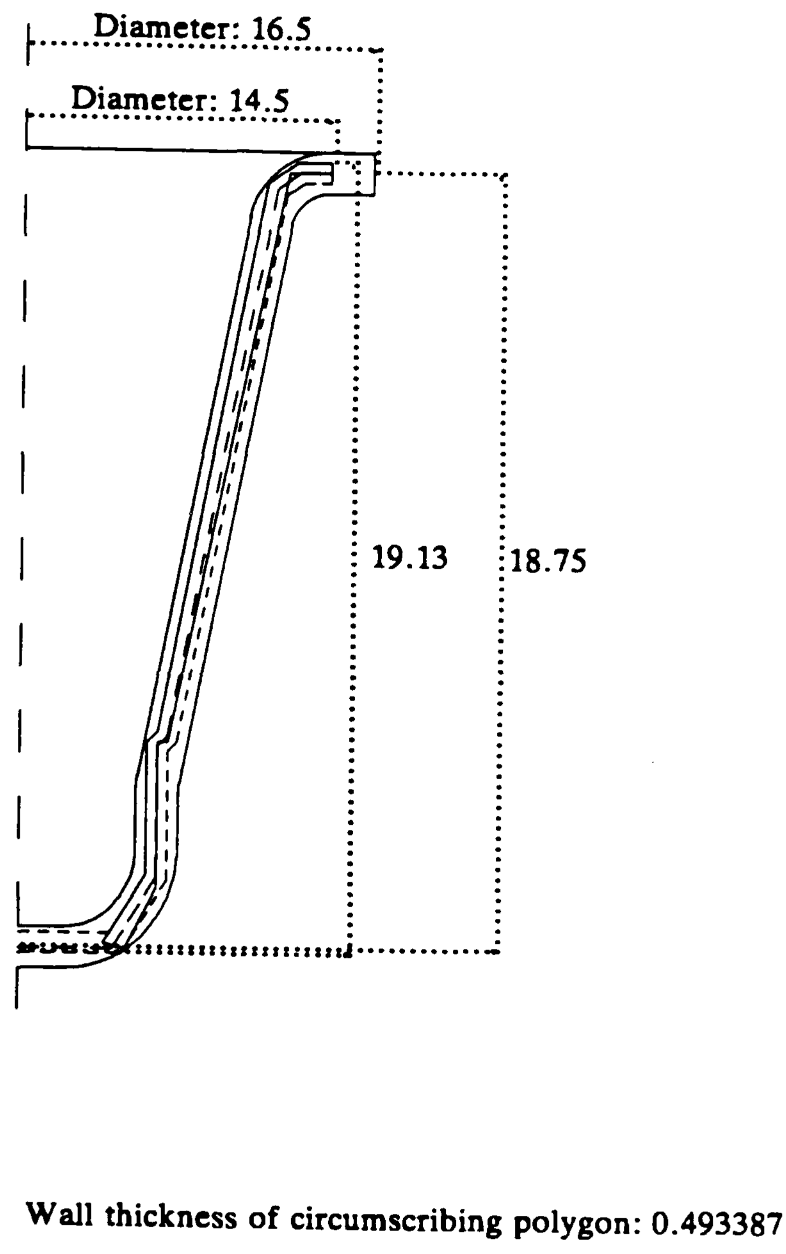


Figure 9-15. Circumscription overview: circumscribing cup, part_c, uniform wall thickness circumscribing polygon and medial

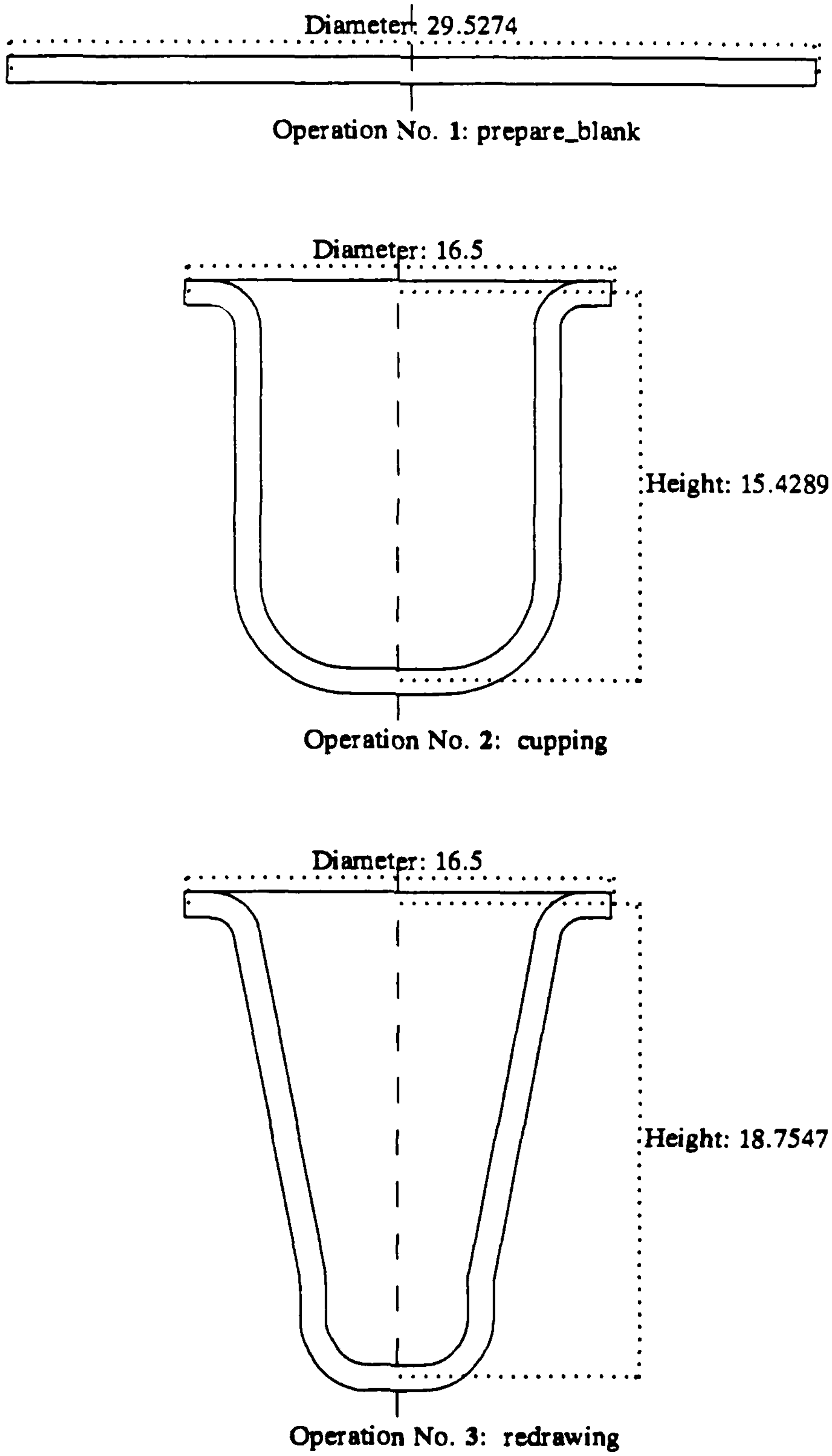


Figure 9-16. Initial deep-drawing process outline for the circumscribing cup

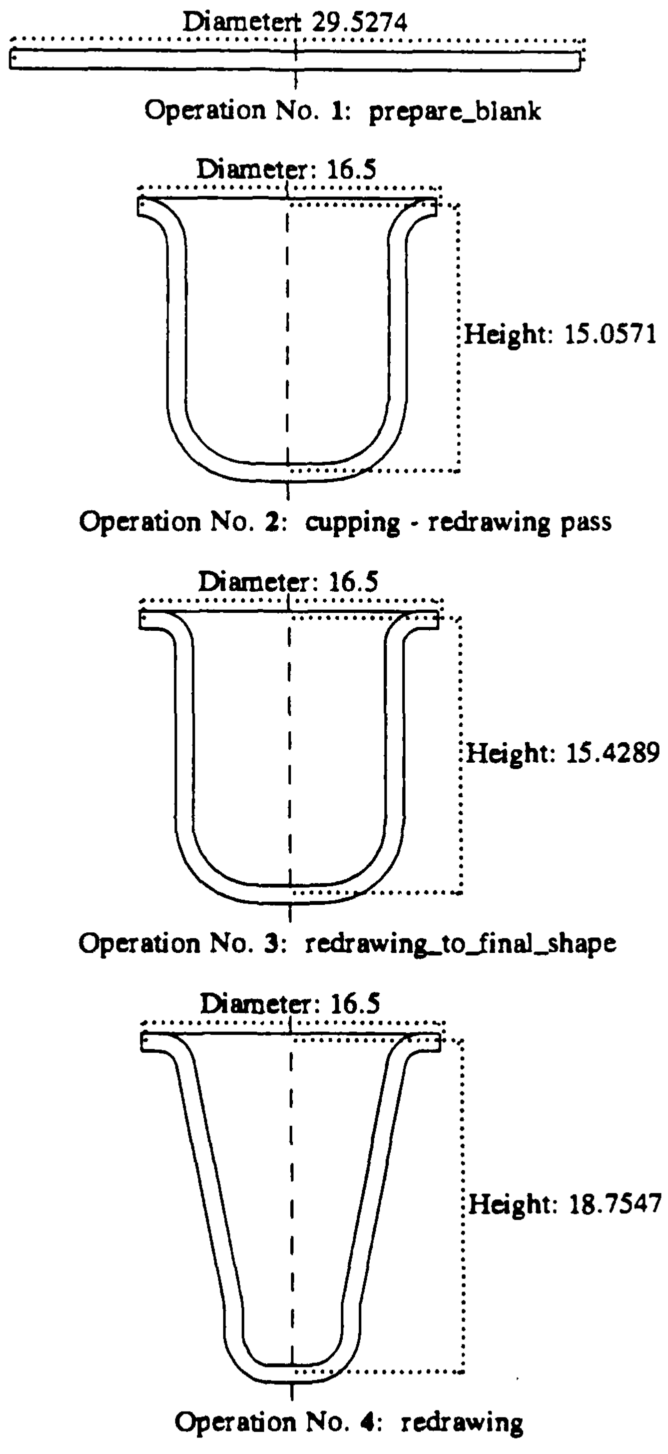
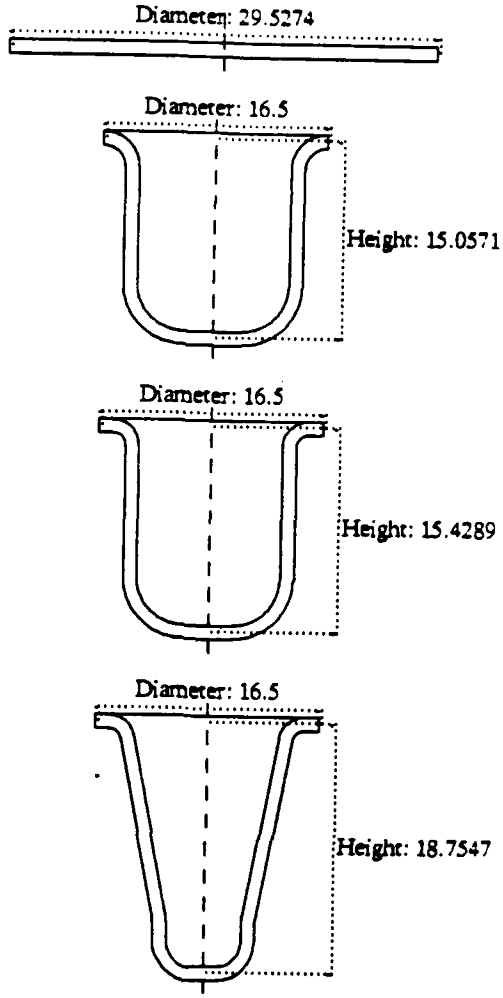
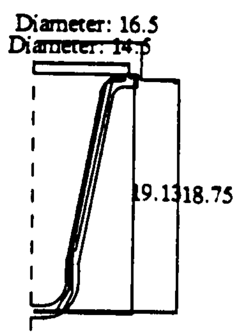


Figure 9-17. Final deep-drawing process outline for the circumscribing cup



Operations 1 - 4: Deep-drawing process outline



Operation No. 5: machining outline

Figure 9-18. Multi-technology process outline for part_c

10. CONCLUSION and FUTURE OUTLOOK

10.1 Overview

The ultimate reason for mechanizing process planning needs no justification. The motivation to automate machining processes; save tedious, recurring, manual work, optimize parameters, utilize more extensive knowledge and expertise, etc., is valid also for metal forming and multi-technology processes. The automatic generation of a process outline is the opening and foremost stage in achieving veritable automatic process planning. This research proposes to show that such goal is feasible though complicated and demanding huge effort. This is manifested by building a system that can generate feasible, realizable and reasonably good process outlines. The generation of process outlines is expected to set a "chain reaction" such as:

— Provide a more powerful tool for thorough checking the producibility of designs at the design stage.

— Discover "new" manufacturing possibilities. These possibilities are not necessarily technologically innovative but they may be overlooked in the course of manual scanning of the manufacturing alternatives.

— Help in the design of dies.

— Provide an initial cost estimate.

But the main lessons of this research are not the conspicuous advantages of implementing an AGMPO-like system. They pertain to

– the process of developing such a system,
– issues that have to be resolved prior to the actual formalization,
– prospective tools to be employed,
– viable techniques that may be extended beyond the scope of the problem

investigated in this research and

- the resources needed to achieve a genuinely automatic process planning system.

Applicability and generality of a research not always do go together. Engineering research is often directed to a class of problems which is quite clearly bounded. Extensive elaboration is required to convert a general methodology to a working application. The AGMPO system is no exception. Once the extent of work that has to be put in was realized, the primary intent has become to illustrate an idea rather than provide a working industrial tool. But even so, to attain the demonstrating capability, huge domain-specific effort in formalizing deep-drawing knowledge, was required. This formalization of the technological knowledge is not directly applicable to other technologies. Nonetheless, the method of establishing and formalizing it can be extended beyond the current application.

Specific conclusions of the research pertain to the techniques developed to attain the automatic process planning. These conclusions are of two realms: the technological part - issues of the deep-drawing knowledge, and the data manipulation part - computational geometry and reasoning techniques. Before these conclusions are outlined, the capabilities of the current AGMPO system are assessed.

10.2 Status of AGMPO

The AGMPO is an experimental system. The overall system, as well as the subsystems, ACDP and AGFPO, serve to experiment with the problem solving techniques rather than provide a working industrial tool. At this stage these systems are neither fully debugged nor optimized.

The ACDP subsystem is very sensitive to the ordering sequence of the rectification rules (both modifications of the medial and smoothing of smoothable medials) in the KB. The AGFPO subsystem has only a part of the technological rules listed in Chap. 3 formalized. The data base - machines, available stock and material properties - is only symbolic, to enable swift instantiation of these predicates.

The meaning of "experimental system" is reflected in the scope of entities that the AGMPO can manipulate and in its size limits. The program is written in C-Prolog. Aside from the efficiency-wise shortcomings of having such a program written in an interpreter language, size limitations affect the performance too. An execution can be carried out as long as the *global stack* is not full. The global stack maintains the active nodes, from the start of the run. Although it could have shed nodes that are bound to be non-backtrackable (like those created by the graphic interpreters), most of its contents is genuinely indispensable. With the current type of lists, stack limits are encountered at about 100,000 nodes. These size limits have serious repercussions even for the simplified parts designed for experimenting with the program. When running the ACDP subsystem by query type 1 (see Fig. 4-1) for parts of ≈ 25 sides, stack limit is typically reached after 2 rectification attempts. The AGFPO module encounters these limits for cups of ≈ 8 elements during the second rectification. Successful generations could, however, be accomplished with an improvization: once an overflow is detected, the rectification rules are rearranged, so that the rectifications rules that have not yet been fired are put first, and the program is reran. This improvization is clearly not in agreement with the very notion of APP.

For the limited scope of parts and processes that are already formalized, the programs produce reasonably good results, notably with the drawing of composite cups. Deep-drawn process outlines generated by the AGFPO subsystem were compared with those in specialized manuals on deep-drawing (especially [Jones]) and the results were remarkably similar. The medial modifying rules in ACDP tend to produce rather thicker cups. This feature is due to the underlying presumption in the ACDP algorithm: the co-linearity of the cup medial and the medials of the circumscribing polygon. In practical circumscription this is not necessarily helpful. To furnish a workable tool, rules for the derivation of a cup medial that is not co-linear with the medial of the circumscribing-polygon have to be formalized. Although conceptually these supplements do not constitute a new idea, they do require a sizable analytic and programming effort.

Expansion of the scope of parts and processes covered by the AGMPO and the contents of the process plan it can produce, beyond the process outline, is

not straight-forward. Basic research issues have to be resolved. These include:

— The inclusion of axisymmetric, *nonmonotonic* parts implies that a set of complementary processes need be introduced. These include: reduction, nosing and bulging processes. New design rules that would define the geometry of the cup, prior to enacting these processes, have to be composed. The ACDP algorithm has to undergo major retrofits. For example, it is presumed throughout the hypothesis stage there, that bisectors between intersecting rectangles can at most form a $\pi/2$ angle with the positive x-axis.

— Expansion to non-axisymmetric parts introduces higher complexity. This stems from the fact that 3D, rather than 2D geometries have to be manipulated. In addition, the TK of composite box-like drawings is much more complicated than of the axisymmetric ones and has not yet been sufficiently investigated, let alone formalized. It is even not yet verified that this TK can at all be put into workable Horn clause forms.

— Deepening the evaluation the AGMPO is currently capable of requires that the technological basis be completed. Some of the important features of the deep-drawing process, such as the thinning of the wall, were neither included in the ACDP stage nor in the process outline generation. Introduction of wall-thickness considerations into the ACDP subsystem can be accomplished by either embedding the feedback from the process planning module, or modifying the circumscribing cup before it is submitted to the AGFPO subsystem. This expansion requires genuine filling of knowledge gaps, like profiling the contour of a drawn cup and not only the extremum changes, i.e. maximum thinning and thickening.

— The deep-drawing system may may be expanded to include other processes, of similar capabilities and scope of formed features, e.g. spinning. This expansion raises the need to translate CAM representations. Conversions of the type:

$$\text{CAM}-\text{representation}_{\text{technology } i} \rightarrow \text{CAM}-\text{representation}_{\text{technology } j}$$

open a new research area. It has not been thus far much addressed because APP at large has been confined to machining only. A tool needed to facilitate this type of expansion is a recognition subsystem that would

determine if the workpiece is workable by the examined technology or not. This step is important to maintain reasonable complexity.

- The AGMPO system ends with the first feasible solution. Many of the deep-drawing rules and the core of the ACDP algorithm is of heuristic nature. It does not guarantee that the first solution is also the best one. It is thus desirable to be able to produce several (all ?) solutions and examine them later, automatically or manually. To answer the question of: "which process outline is better" automatically, a new component, not included thus far in the system, has to be developed. The need to produce several solutions introduces the research issue of: "when to terminate generation".

10.3 Process Planning Methodology

Since no universal automatic process planning methodology has yet been revealed (and is not likely to), aspects of a specific system, e.g. part representation and plan synthesis tactics, have to be derived from the TK. The G&TR tactic and its particular applications in the automatic circumscription and the process outline generation have only been accomplished after a study of the TK. The extraction and formalization of the TK of additional technologies, say spinning, is expected to be much easier, as a framework of analysis has been established in this research.

An automatic process planning system requires the coalition of many disciplines, techniques and means. One, or few, underlying principles cannot cover the minute details of the system. Techniques employed by the AGMPO system such as: computational geometry, rule based representation, pattern recognition, CAD-CAM links, substantiate this idea. Efficiency considerations also play a major role, with the aforementioned stack limit problem being one instance. Various parts of the process planning system have to be implemented in different programming languages. Contemporary symbolic programming languages do not meet the requirements for computations. External programs, written in nonsymbolic languages, have to be embedded to, perform the fine computation parts as well as save stack space.

The complex structure of an automatic, multi-technology, process planning system is amplified by the diversity of means available to define process

capabilities. Two instances of this diversity are:

— Every process and technology have their individual CAM representation. The KB of a certain technology can manipulate features of its dictionary only. These are not necessarily common to other processes and technologies.

— Whereas de-machining can be formalized with relative ease - the number of reasonable geometries the examined feature could have been machined form is limited - de-forming is much more indeterminate. Thus, simplifying assumptions about the previous shape in de-forming are often unsatisfactory. Furthermore, if a G&T tactics is used, the complexity of generation is increased. In the case of deep-drawing and machining, a cup of a formable type is not guaranteed to be realizable or formable at a reasonable cost. Rejection of a hypothesized cup would return the generation to the preform design stage, with the ensuing complexity ramifications.

Structuredness is generally helpful in formalizing the TK. It is, however, vital if a sizable system has to be built. Structuredness pertains to the organization of files, differentiation between abstract formulations and instantiated rules, and the structure of individual rules. Formulations of new rules with relators that do not comply with the existing relators and/or random insertion of rules into the KB would not allow the buildup of a sizable system to be attained and make updates practically impossible. This pertains to any type or extent of expanding the KB: It would have become an impossible job, if with every update of the TK the AGFPO program had to be changed, rather than having the new rules easily appended or their current version in the KB modified.

Effectiveness of the techniques employed in AGMPO is studied within the domain of axisymmetric deep-drawing and machining processes. Conclusions are, however, applicable to other technologies, especially to those which are similar in the structure of the TK.

— TK of deep-drawing can be extracted and put into a generalized Horn clause form, with "generalized" referring to *facts* being defined as Horn clauses of empty RHSs. Generalization makes tabular data amenable to be represented in rule form too.

— The technological rules present themselves in categories of usage. The categories identified in the TK of deep-drawing are: "generate", "test", "rectify" and "computations". These categories are not necessarily the ones that will emerge with formalization of other technologies, though the grouping of rules in those TKs may be carried out in a similar way.

— G&TR is a viable APP technique if applied to a proper pattern of TK. G&T is a natural way a PP expert draws on his experience. One may first come out with a diagnosis of the features of the required part and then follow with the generation of a simple solution that can easily be modified and adapted to a variety of parts. G&TR presumes that the first "guess" of the expert may not be the exact solution but that it is essentially good. Desirable results may thus be attained with relatively minor modifications of the first solution.

— The automatic design of the preform is an integral part of a multi-technology PP. It is stipulated that the preform be manufactured by a set of forming processes, and the final geometry by machining.

— The automatic design of a formable preform can be formulated as a computational geometry problem: circumscription emulates de-machining. The circumscribing preform can be designed such that it satisfies some constraints of the TK and *locally* optimizes other.

— RBSs make useful mechanisms in supervising constraint-based circumscriptions, where no explicit optimum is available. In this case circumscription may be attempted by several heuristics, though none of them guarantees a feasible solution.

— The automatic generation of the *test* in G&T plan synthesis systems is an integral part of the synthesis. If each of the individual tests is valid within a certain set of conditions, and the relationship between the tests is conjunctive, the inclusive test can be constructed automatically. The automatic construction of the inclusive test rule is based on a domain-independent abstract formulation. It saves the tedious work of formulating a test for each set of conditions: {parts, materials, deformation processes and strain history}. From the automatic reasoning standpoint, the subsystem for the automatic generation of the inclusive test rule is an

instance of a rule generator.

— The depth-first search can be efficiently used in plan synthesis PP systems. It is applicable when the order of the predicates in the RHS, of the lowest level rules, conforms with the following:

a. Leftmost predicates are "trivial": either "ground" instances (mainly data-base instantiations) or list manipulations.

b. The predicates that are bound to be instantiated by several items in the KB come immediately to the right of the "trivial" predicates, and the order of instantiation will comply with the prospective final configuration.

Hence the depth-first search can be successful if it is linked to an instantiation in accordance with a predefined priority. This order, however, has to be modifiable, - a feature that is achieved in AGMPO by a combination of *retractions* from the working memory and *reconsultations*. This finding is emphasized since the prevailing belief is that "best-first" search is the only practical mechanism for sizable plan synthesis spaces.

10.4 Deep-Drawing Knowledge Gaps

The formalization of deep-drawing knowledge revealed quite a few significant gaps the filling of which is crucial for the setting up of an automatic design system as well as for conducting manual process planning. This finding is true even with the limited scope of parts and processes on which the TK was formalized. Knowledge gaps will grow with any expansion of the range of parts, strain tensors and processes. Some prominent knowledge gaps are listed below. Others are abundantly mentioned in the context when they are formalized in Chap. 3.

— The relationship between wall-thickness and drawing ratios.

— The definition of conicity severity as a function of: wall thickness, cone angle, cone length, cone diameter and material.

— A measure of predicting stretching in the region wrapping punch rounding.

— The detailed profile of wall thickness strain in simple cupping and redrawing. In the next stage this profile would be sought for more

compound drawings.

— The exact contributions of bending and unbending to strain hardening and consequently to the accumulated limit redrawing ratios.

— The range of shape elements that can be deformed by *sizing* and the preparatory geometry needed to have it applied.

— A design practice w.r.t. drawing several adjacent tapered elements.

The filling of these knowledge gaps would obviously benefit manual process planning too.

10.5 AI Tools

This research provides insight into the potential problems future APP may face with some AI tools and mechanisms. In addition, some needs w.r.t. the existing AI tools are manifested. Some of them imply not only the need for enhancement of packages, but for basic research.

Prolog for Process Planning

Prolog makes an attractive tool for the manipulation of rules. It is based on a built-in theorem proving facilities and provides a backtracking mechanism. It is however, an interpreter language (the AGMPO uses the C-Prolog version), - thus grossly inefficient for large search spaces, and has other deficiencies that cannot be ignored.

Computational inadequacy:

— The C-Prolog has no floating point representation, and its numerical approximations of various functions make the comparison of numbers all but impossible. For example:

"X is 1/1000" would be represented as: "X = 0.000999999", but "X is 1/1000+1, Y is X-1" will yield "X = 0.001".

One frequent flaw with these inconsistencies, is that two parallel lines that encounter two different representations may be erroneously declared not parallel. Deviations are amplified with trigonometric functions.

— Small numbers are represented in the logarithmic form. This form is not recognized by graphic packages and thus requires additional refinements before pipelining into graphic filters.

— C-Prolog does not accept direct instantiation of negative numbers. This can be overcome by introducing intermediate variables, but forces, again, additional intermediate refinement.

The *global stack*, which holds active nodes, grows steadily throughout the execution, the user not being able to control its contents. It is thus filled with redundant many nodes and encounters a premature overflow followed by an interruption of the execution. A mechanism that would differentiate between nodes that are important to backtracking and those that are not, would thus be greatly helpful.

One is quite limited in controlling the search, once a consultation started. The "*!-fail*" (cut-fail) mechanism fails the whole functor within which it is defined. There is no straight-forward way of halting an evaluation of a functor and resuming the search for the same functor in the KB. This loads RHSs of predicates with great many halting mechanisms and complicates the programming.

The slowness of execution and huge memory the Prolog interpreter occupies can be overcome with the introduction of dedicated Prolog machines, like the Lisp machines.

Reasoning Methods

It is widely accepted that there is no a-priory way of detecting possible *contradictions* a rule based system may run into. Building and expanding the KB poses a limited requirement that may be met: detection of *first-degree* contradictions and *overlapping* of rules.
For example, in the following system:

sentence 1: a :– (b,c);d.

sentence 2: a :– d.

sentence 2 is redundant and should be removed.

The extraction of the technological knowledge remains largely an art and the very basic operation of formulating the rules is still the least formalized activity. A system that could take a set of facts and some recognized rules and find out the missing rule will greatly upgrade APP. This research has made it clear that real progress in formal APP is linked with some form of formal extraction of the technological knowledge.

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APPENDIX A
Project Staff in 1985-1986

Appendix A

Project Staff in 1985-1986

Faculty

M. M. Barash, Ransburg Professor of Manufacturing and Professor of Industrial Engineering	Principle Investigator & Project Director
C. R. Liu, Professor of Industrial Engineering	Principal Investigator
K. S. Fu*, Goss Distinguished Professor of Engineering (Elec.Eng.)	Faculty Associate
J. Modrey, Professor of Mechanical Engineering	Co-Principal Investigator
A. L. Sweet, Professor of Industrial Engineering	Co-Principal Investigator
W. Stevenson, Professor of Mechanical Engineering	Faculty Associate
W. Johnson**, Visiting Professor of Industrial Engineering	Faculty Associate
J. L. Batra†, Visiting Professor of Industrial Engineering	Faculty Associate

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Graduate Research Assistants

*P. Chen
Y.C. Chou
P. Ferreira
*R. Khanna
G. Lang
*S.K. Lee
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*Y.T. Lin
J. Lopez
*D. Noller
Y.S. Ouyang
U. Roy
S. Shodhan
R. Srinivasan
*R. Venugopal
M.C. Wu
*J. York
Y.C. Yu

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